STOCHASTIC METHODS FOR SURFACTANT-POLYMER FLOODING AND WELL PLACEMENT OPTIMIZATION

BY

HASSAAN AHMED

A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING DEPARTMENT

November, 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **HASSAAN AHMED** under the direction his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PETROLEUM ENGINEERING.**

Dr. ABEEB A. AWOTUNDE
(Advisor)

Dr. ABDULLAH S. SULTAN
Department Chairman

Dr. HASAN Y. AL-YOUSEF
(Member)

Dr. SALAM A. ZUMMO
Dean of Graduate Studies

Dr. ABDULLAH S. SULTAN
(Member)

25/11/13
Date

عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

Dedication

To my dear parents and sister for their endless love and support

ACKNOWLEDGMENTS

All praise is to ALLAH Almighty who made it possible for me to accomplish this research work successfully.

I would like to thank my advisor Dr. Abeeb A. Awotunde for his guidance, support and patience. His encouragement and insights enabled me to work towards getting desired results and to overcome the problems along the way. I would also like to thank Dr. Abdullah Sultan and Dr. Hasan Y. Al-Yousef for their generous help and support for this project.

I would also like to express my gratitude to all the faculty members of the Petroleum Engineering Department at KFUPM. To all of them, I appreciate what they have done to help me in my scholastic and professional growth.

I would like to acknowledge the Centre of Petroleum & Minerals (CPM) at Research Institute (RI) in KFUPM and Saudi Aramco for arranging financial support of this research project (CPM-2297).

I am grateful to Information Technology Centre (ITC) at KFUPM for providing the computing resources used in this work. Special thanks to Mr. Mohammed Akbar Ali for helping me by providing the computing nodes.

I acknowledge my friends and well-wishers, whom I have not mentioned above and whose best wishes have always encouraged me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CMAES	:	Covariance Matrix Adaptation Evolutionary Strategy
DE	:	Differential Evolution
IWO		Invasive Weed Optimization
NPV		Net Present Value
SP		Surfactant Polymer
UR		Ultimate Recovery
WPO		Well Placement Optimization

ABSTRACT

Full Name : Hassaan Ahmed

Thesis Title : Stochastic Methods for Surfactant-Polymer Flooding and Well Placement Optimization

Major Field : Petroleum Engineering

Date of Degree : November, 2013

Chemical flooding is one of the most important enhanced oil recovery (EOR) techniques for the current decade and a great number of fields in the world have been produced with chemical injection into the reservoir. There has been a revival in chemical enhanced oil recovery techniques during the last few years because of the advancements in technology and high oil prices. Also with the depletion of resources, there exists a need to efficiently design production strategies with effective EOR mechanisms. Surfactant-Polymer flooding in one of the successful EOR techniques which alters the wettability of the rock and controls the mobility of the liquids.

On the other hand, well placement is one of the main steps in field development plan. A well planned EOR process can be spoiled if right candidate wells are not selected for the EOR process. Therefore the selection and optimization of EOR process in conjunction with well placement optimization is needed for effective ultimate recovery process.

The main objective of enhanced oil recovery is to recover as much oil from the reservoir as possible within economic limits. The maximum oil that can be recovered from the reservoir can be evaluated using ultimate recovery factor (URF) while net present value (NPV) serves as the economic indicator all over the project life.

This research uses Surfactant-Polymer (SP) flooding as the chemical EOR process. The objective of the research is to select the best stochastic optimization technique for the Surfactant-Polymer flooding process with well placement optimization. It includes the simulation of SP flooding process for different scenarios having net present value (NPV) and ultimate recovery factor (URF) as the objective functions while the time for water-flooding, surfactant flooding, polymer flooding, surfactant and polymer concentrations in injection wells, and well locations served as the optimized variables.

The simulation and optimization study has been done using Eclipse reservoir simulator and MATLAB.

The results indicate that stochastic optimization techniques can be used to find the optimal combination of operational parameters that give high Net Present Value (NPV) and Ultimate Recovery (UR).

ملخص الرسالة

الاسم الكامل: حسان احمد

عنوان الرسالة: الطرق العشوائية للغمر باستخدام البوليمرات ذات الفاعلية السطحية وتموضع الآبار الأمثل

التخصص: هندسة البترول

تاريخ الدرجة العلمية: نوفمبر2013

إن الغمر الكيميائي يعتبر من إحدى تقنيات الإستخلاص المعزز للنفط للعقود الحالية من الزمن وهناك عدد كبير من حقول النفط حول العالم تُنتج بإستخدام الحقن الكيميائي للمكمن. هناك إنتعاش كبير في استخدام تقنية إستخلاص النفط المعزز بالطرق الكيميائية خلال السنوات الأخيرة وهذا يعود إلى التطورات التكنولوجية وكذلك إلى سعر النفط العالي. أيضا ومن خلال إستنزاف المصادر فإن هنالك حاجة ماسَة لتصميم إستراتيجية فاعلة للإنتاج مع آليات فعّالة لإستخلاص النفط المعزز. إن الغمر بإستخدام البوليمرات والسيرفاكتانت ذات الفاعلية السطحية يُعتبر إحدى تقنيات آليات إستخلاص النفط المعزز الناجحة والذي يُغير قابلية تبلل الصخر المكمني وكذلك يتحكم بإنتقال الموائع.

في المقابل فإن تموضع الآبار يُعتبر من إحدى الخطوات الرئيسية في تطوير خطط حقول النفط. إن عملية إستخلاص النفط المعزز لبئر نفطي يُمكن أن تكون سيئة اذا لم يتم إختيار الآبار المرشحة لعملية الإستخلاص المعزز بشكل صحيح. لذلك فإن الإختيار الأمثل لعملية الإستخلاص المعزز للنفط بالتزامن مع التموضع الأمثل للآبار يكون ضروريا لكي تكون عملية الإستخلاص فعالة في نهاية المطاف.

إن الهدف الأساسي لإستخلاص النفط المعزز هو لإسترداد أكبر كمية نفط ممكنة ضمن الحدود الإقتصادية. إن كمية النفط القصوى التي يمكن إستخلاصها من المكمن يمكن تقديرها عن طريق إستخدام معامل الإستخلاص النهائي في حين تُعتبر قيمة الصافي الحالية هي المؤشر الإقتصادي لمدة المشروع الكُلية.

في هذا البحث تم إستخدام الغمر بإسلوب البوليمرات والسيرفاكتانت ذات الفاعلية السطحية كعملية إستخلاص نفط معزز كيميائية. إن هدف هذا البحث هو لإختيار أفضل تقنية مثالية لعملية الغمر البوليمري ذو الفاعلية السطحية بالتزامن مع عملية التموضع الأمثل للآبار. إن هذا البحث يشتمل على محاكاة عملية الغمر البوليمري ذو الفاعلية السطحية للعديد من التصورات والتي تكون فيها قيمة الصافي الحالية وكذلك معامل الاستخلاص النهائي هي الأهداف الاساسية بينما تمثل

المعاملات التالية أبرز المتغيرات في عملية المحاكاة: زمن الغمر المائي, الغمر البوليمري ذو الفاعلية السطحية, الغمر البوليمري, تركيز الفاعلية السطحية, تركيز البوليمر في آبار الحقن, وكذلك مواقع الآبار.

إن عملية المحاكاة و التحسين الأمثل تمت عن طريق إستخدام برنامج المحاكاة (Eclipse) وكذلك برنامج ماتلاب (MATLAB).

لقد أوضحة النتائج أن تقنية التحسين العشوائية يمكن إستخدامها لإيجاد أفضل مزيج بين معاملات التشغيل التى تعطي أعلى معامل استخلاص ممكن.

CHAPTER 1

INTRODUCTION

According to the 2010 report of World Energy Counsel (WER), the global recoverable reserves of crude oil and natural gas liquid at the end of year 2008 are around 1239 billion barrels i.e. 163 billion tones. The Middle East shares 61% of the total reserves and remains vital in the energy sector. The rest belongs to Africa 11%, South America 10%, Europe 8%, Asia 5%, and North America 5%; where Europe includes the whole of the Russian Federation. However, it is uncertain to predict the amount of recoverable oil and gas exclusively. On the other hand, the increase in the global population increases the demand for energy and has resulted in high oil prices during the last few years. It is therefore needed to devise more efficient ways of oil production and increase ultimate recovery. The advancement in the chemical EOR technology is able to cater this issue. Moreover, the improvement in reservoir characterization and formation evaluation methods; reservoir modeling and simulation techniques; and reservoir management significantly affects the ultimate recovery from the reservoir.

When the reservoir has gone through the primary recovery stage, water-flooding is used as a secondary recovery mechanism. In water-flooding, water is injected into the reservoir to sweep the remaining oil inside the reservoir. Water-flooding can increase recovery from 1% to 40% range (Schlumberger Manual, 2010). Due to the immiscible nature of oil and water, water cannot completely displace oil from an oil reservoir. Due to the viscosity difference of oil and water, the mobility of water is higher than the mobility of oil. Therefore, water often bypass the oil through high permeability zones in the reservoir. Thus, there is a considerable amount of oil left after water-flooding which is named as remaining oil saturation. It means that regardless of the amount of water cycled through the system, the oil saturation will not be reduced below remaining oil saturation. The remaining oil saturation can be divided into two classes

1. Residual oil to the water flood
2. Oil bypassed by the water flood

To reduce remaining oil saturation in the reservoir and increase the ultimate recovery, polymer, surfactant, and surfactant-polymer flooding are used.

In polymer flooding, a water-soluble polymer is added to the injected water stream. The addition of polymer to the water increases the effective viscosity of water and hence decreases the mobility of injected water. The decrease in mobility results in a favorable fractional flow curve for the injected water which causes efficient sweep and reduced viscous fingering. In high permeable zones of the reservoir, plugging effect due to passage of polymer occurs which diverts the injected water into less permeable zones of the reservoir. This reduces the rock permeability to water while the rock permeability to oil remains unaltered. Both these effects of increased viscosity and reduced rock permeability to water result in high sweep efficiency of polymer flood and hence higher ultimate recovery.

In surfactant flooding, surfactant (Surface Active agent) is added into the injected water stream. Surfactant reduces the interfacial tension (IFT) by adsorbing at the oil-water interface. This reduction in IFT reduces the capillary pressure and enables the injected water to displace the entrapped oil which was not recovered during the secondary recovery process.

Surfactant-Polymer (SP) flooding combines the advantage of mobility control by the use of polymer which increases the sweep efficiency of the flood and the interfacial reduction by the surfactant which enables us to recover some of the residual oil. In SP flooding, surfactant and polymer are injected sequentially into the hydrocarbon reservoir. Injection of surfactant alters the wettability of the rock by adsorbing onto the rock surface which is followed by the polymer solution. Polymer solution controls the mobility of the chase water followed by it.

Before the selection of enhanced oil recovery method for the reservoir, a detailed field development plan for the production life of the reservoir should be developed. Well placement in the reservoir is one of the most important steps and challenging task in field development process. After having a reliable geological model and reservoir characterization, the next task is to have optimum number of injection and production wells which will fulfill the production needs as per the production plans. The conventional practice of finding the optimum location for the wells is by manually changing the position of the wells in the reservoir using reservoir simulator based on the engineering knowledge. In recent times, advancements in stochastic optimization algorithms have made it possible to locate the optimum positions of the wells in the reservoir with improved efficiency.

With the increasing interest of Saudi Aramco in SP flooding for the giant fields (Fig. 1.1), research in the area of SP flooding needs attention. After the screening process of the EOR mechanisms for the field (Fig. 1.2), and selection of suitable surfactant and polymer, the next step is the process optimization. Process optimization is defined as the optimization of all parameters which affect the efficiency of the process.

Chapter 2 concludes the literature review in the area of surfactant flooding, polymer flooding, surfactant polymer flooding, well placement optimization and application of stochastic algorithms in engineering problems.

Chapter 3 forms the theoretical background of the stochastic evolutionary algorithms used in this research. A detail description of the algorithms is also mentioned.

Chapter 4 mentioned the statement of the problem, research objectives, reservoir model, parameters to be optimized and objective functions.

Chapter 5 is for results and discussion where results of all the cases are discussed and compared on the basis of objective function values. The efficiency of the evolutionary algorithms used in this research also compared for different cases.

Chapter 6 gives the conclusion of the research.

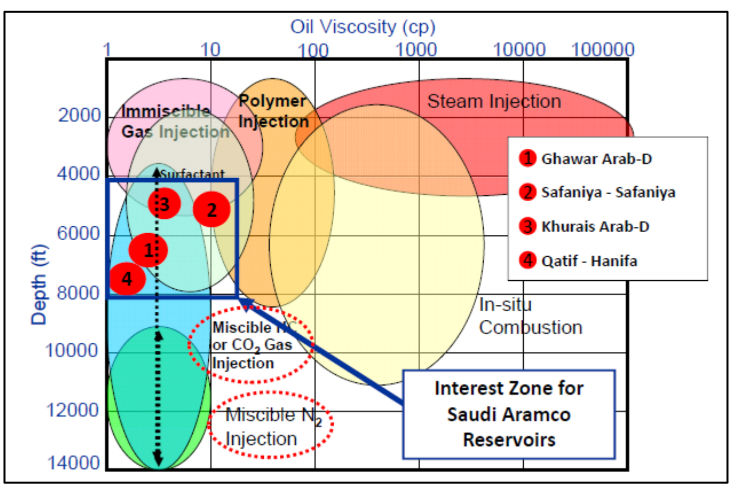


Figure 1.1: Interest Zone for Saudi Aramco Reservoirs (Kokal, Saudi Aramco)

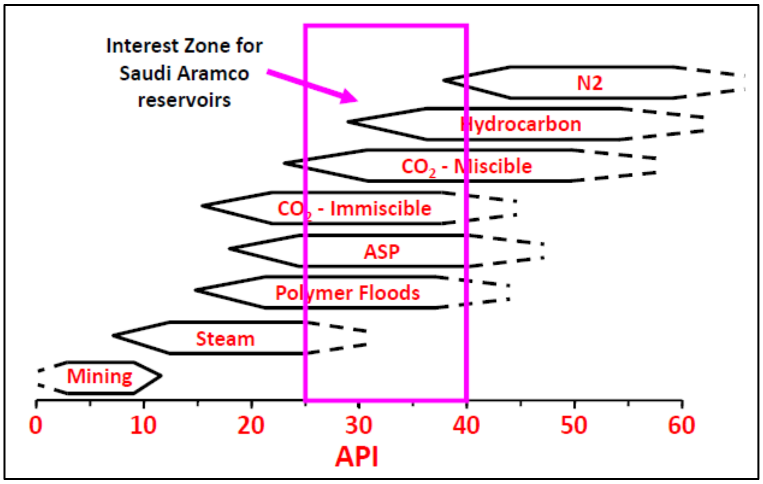


Figure 1.2: EOR Screening (Kokal, Saudi Aramco)

CHAPTER 2

LITERATURE REVIEW

In chemical EOR, polymer flooding is one of the most common and widely used methods. Commercially, polymer flooding was first used in 1960s and uptill now it is considered as an effective method of enhanced oil recovery (Pope, 2011). In polymer flooding, polymer solution is injected into the reservoir with water. The main objective of polymer flooding is to decrease the mobility of injected water. It causes reduction in fractional flow of injected water and hence improves the sweep efficiency and reduces viscous fingering. It also plugs some of the high permeable zones thus forcing the water to flow through the zones which remained upswept during water-flooding (Shah and Schechter, 1977; Needham and Doe, 1987). The decrease in mobility of injected water is due to the viscosity difference of polymer and injected water and rock permeability to water. The viscosity of injected water increases as the concentration of polymer increases while after passage of this viscous injected water into the reservoir rock, the rock mobility to water decreases while for oil it remains unaltered (Schlumberger Manual, 2010).

The most widely used polymer for polymer flooding is Polyacrylamide (Zheng et al., 2000) or copolymers or hydrolyzed polyacrylamide (HPAM). The quality of these polymers has drastically increased in recent times as compared to the one used in 1960s (Pope, 2011).

The use of polyacrylamides is due to its capability to be used in salinity ranges from 700 to 2500 ppm and its low price (Shehata et al., 2012). To produce an incremental barrel of oil, 1 to 2 pounds of HPAM polymer is used. In terms of economic analysis, oil prices in early 1970s were $3 per barrel while that of polymer was $1.5 per pound. Today, oil is about $100 per barrel while the price of HPAM polymer remains about the same (Seright, 2010; Pope, 2011). Hence, the improvement of quality and reduction in price of these polymers justifies the use of polymer flooding as an economical flooding process.

Similar to polymers, surfactants are also used for EOR processes. The concept of using surfactant for the enhanced oil recovery was introduced in late 1920's and early 1930's (De Groot, 1930). Although the effectiveness of the surfactants on theoretical grounds were never been questioned but issues regarding its feasibility in industrial scale application remain unanswered. Mass production of ionic surfactants in 1960's significantly increased the use of surfactant flooding in enhanced oil recovery and it became one of the most effective methods of producing oil left after primary and secondary recovery (Lakatos et al., 2007). Later on advancements in the use of surfactants were made by using different configurations (Holbrook, 1958; Holm and Bernard, 1959).

The entrapment of oil in the reservoir during primary and secondary production phases is due to the dominant capillary forces. Therefore, aqueous surfactant (Surface-Active agents) solution is injected in the reservoir to reduce the interfacial tension between oil and water phases (Atkinson, 1927). Hence, surfactant works on a mechanism of decreasing interfacial tension between oil and water and this increases the mobility of the resident oil thereby improving the displacement efficiency (Xu et al., 2011). Recently viscoelastic surfactants have been developed which serves, in both, lowering interfacial tension and mobility control (Lakatos et al., 2007).

As discussed above, polymer flooding can improve the sweep efficiency but does not affect the wettability alteration mechanisms. However, if surfactants are added to polymer flood then the overall system can increase the sweep efficiency as well as microscopic displacement efficiency. This is the reason why the surfactant-polymer (SP) flooding is considered as the most effective enhanced oil recovery mechanism (Wang et al., 2010; Gao et al., 2010). Initially it was proposed the use of alkali with SP flooding but later on researchers found that alkali used to react with minerals present in the rock and form scales (Katsanis et al., 1983). Furthermore, it was observed from production fluids that alkali formed stabilized emulsions which are difficult to break (Yang et al., 2004). Due to the increase in salt concentration, polymer adsorption on the rock surface increases. This effect will be more pronounced in case of divalent cations e.g. calcium or magnesium ions. The increase in salinity causes decrease in viscosity and elasticity of polymer and decrease in sweep efficiency (Dang et al., 2011). These are the reasons to avoid alkali in SP flooding.

Recent research proved that by finding the critical values of surfactant interfacial tension (IFT) and polymer viscosity for surfactant-polymer flood, maximum oil recovery can be achieved. However, the critical value of IFT for surfactant is not the lowest IFT and the critical value for polymer viscosity is not the maximum value which opposed the conventional belief regarding these two properties. This phenomenon is due to the fact that the oil recovery is the product of displacement efficiency and sweep efficiency. Hence, in heterogeneous reservoirs we have to design the flood such that the overall effect of sweep efficiency and displacement efficiency is towards the maximum oil recovery (Wang et al., 2010).

On the other hand, most of the hydrocarbon producing fields around the world are reaching to maturity, hence developing a need for reservoir engineers to optimize reservoir performance. In this context, one of the critical and challenging problems is the efficient placement of the wells in the reservoir. Many variables can dictate the decision for well placement which includes reservoir rock and fluid properties like rock permeability to fluids and porosity, reservoir architecture, reservoir heterogeneity, well type, production rates, and economic criteria. After thorough understanding of these variables, the following questions can be answered (Ding, 2008; Bukhamsin et al., 2010; Gűyagűler et al., 2000; Forouzanfar et al., 2010)

- What will be the well type (vertical, horizontal or multilateral)?
- In case of horizontal well, what will be the length of the horizontal section?
- In which direction the horizontal well should be drilled?
- In case of multilateral well, how many laterals are needed and what are their lengths and directions?
- What will be the depth and type of completion?

The evolution of horizontal and multilateral wells increases the dimensions of the optimization problem and hence making it a key factor to affect project economics.

Optimization is a common area of concern for all engineering disciplines. In general, there are two broad categories of optimization; stochastic and deterministic. Deterministic methods require enormous computational efforts and their application is limited to problems having limited number of dimensions. Since most of the problems in nature are multi-dimensional and sometimes it is difficult to correlate the variables. This is the motivation to use stochastic algorithms for solving problems having high dimensions with greater efficiency. The optimization problem can be solved using two approaches of stochastic algorithms namely the population-based approach (Evolutionary algorithms, Swarm-Based algorithms) and the single-agent approach (Tabu Search, Simulated Annealing, etc.). The global optimization approach uses the iterative improvement of a population of solutions while the local optimization starts with single solution and employ different techniques to improve it to the optimized values. These techniques are classified under the meta-heuristics which mostly employ randomization to solve a given optimization problem (Fig. 2.1).

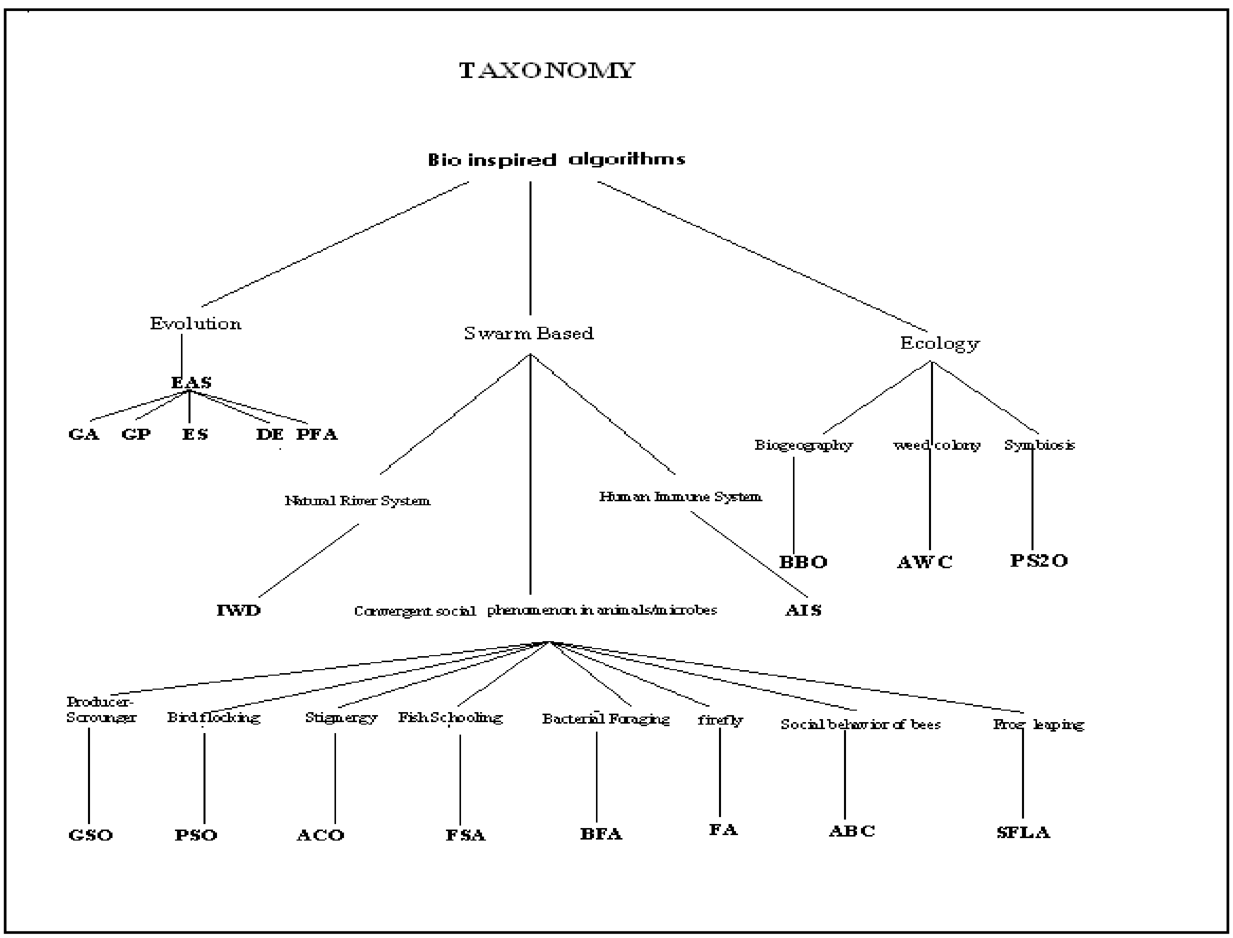


Figure 2.1: Taxonomy and nomenclature of various bio inspired optimization algorithms grouped by the area of inspiration (Binitha and Sathya, 2012)

In recent times, economic studies have been carried out and selection criterions have been developed for well types, performance, and placement selection. Feasibility analyses have been done for the placement of horizontal and vertical wells in the reservoir (Guo et al., 1993; Aanonsen et al., 1995; Dejean et al., 1999; Yeten et al., 2002; Gűyagűlar, 2003; Seifi and Kazemzadeh, 2008; Hassani H. et al., 2011). Different optimization methodologies have been used for the determination of optimum location of these wells. The techniques used are response surface methodology (Aanonsen et al., 1995; Dejean et al., 1999; Hassani H. et al., 2011) and meta-modeling based methodology (Seifi and Kazemzadeh, 2008; Hassani H. et al., 2011). Furthermore, multiple optimization techniques are combined to form a single hybridized algorithm which improves the efficiency of the process. The techniques used in hybridization are genetic algorithm, tabu search and polytope algorithm (Yeten et al., 2002), kriging proxy, neural networks, polytope algorithm (Gűyagűlar, 2003), and genetic algorithm and polytope algorithm (Nakajima et al., 2003; Badru and Kabir, 2003).

Therefore, in order to address the optimization problems in flooding process and well placement, this research discusses three stochastic optimization algorithms namely Covariance-Matrix Adaptation Evolutionary Strategy (CMAES), Differential Evolution (DE), and Invasive Weed Optimization (IWO). A brief description of these algorithms is presented hereunder.

Covariance Matrix Adaptation Evolutionary Strategy (CMAES) is a population based stochastic search algorithm which is considered as the state of the art algorithm for continuous optimization (Loshchilovet al., 2011). In CMAES a population of λ points are samples at each iteration g according to a multivariate normal distribution. Then objective function ‘f’ of these λ points is evaluated and the parameters of the multivariate normal distribution are updated based on the results of objective function. The process of updating the multivariate normal distribution continues until the stopping criteria does not achieve (Hansen, 2011)

The inherent invariance property of CMAES makes it a powerful stochastic technique which is widely used in solving optimization problems. Recent advancements in CMAES have further improved the technique (Loshchilov et. al., 2011; Bouzarkouna et. al., 2011; Hansen, 2011). For example, the addition of multi-objective optimization evaluation (Igel et. al., 2007) enables the technique to handle multiple conflicting objectives and come up with an optimum solution. CMAES is also used in solving the typical multidisciplinary problems of expendable launch vehicle related to space transportation. The disciplines include propulsion system, aerodynamics, mass budget, trajectory integration and control. CMAES was tested on a two-liquid-stage launcher with solid boosters. The technique is then compared with the Non-Dominated Sorting Genetic Algorithm NSGA-II in which CMAES surpasses NSGA-II (Collange et. al., 2010). In petroleum engineering problems, CMAES is used in solving optimization problems involving well placement in a hydrocarbon reservoir (Bouzarkouna et. al., 2011). In many problems, CMAES is compared with genetic algorithm (GA) which is famous for well placement optimization problems. Results showed that CMAES outperformed GA (Bouzarkouna et. al., 2012; Ding, 2008).

DE is a member of evolutionary algorithms based on population-based stochastic global optimization. The algorithm is known for its robustness, simplicity, less number of control variables and fast convergence. The property of DE which distinguishes it from other algorithms is its unique scheme for vector perturbation using vector differences to produce new generation.

DE starts with the initialization of random particles (parents) within the search space. These initial particles (parents) take part in the process of mutation and crossover to come up with a new set of particles (offspring). Mutation is done by taking difference between randomly selected vectors (parents) to generate the new solutions (offspring). To further perturb this new solution, crossover method is used by copying offspring and its parent to a new vector named as trial vector. Using certain crossover factor, individual parameters of these solutions are perturbed and selected. Selection method is employed between the old solutions and their corresponding trial solutions by computing objective function value for trial solutions. If the later performed better, they will be selected otherwise the old solution retained (Storn and Price, 1995; Storn, 1995; Storn and Price, 1996; Storn, 1996a; Storn, 1996b; Lampinen and Zelinka, 1999; Lampinen, 2001, Karaboga and Okdem, 2003).

Invasive weed optimization (IWO) is a numerical stochastic evolutionary algorithm inspired from weed colonization. To understand IWO, it is necessary to understand the basic properties of the weed colonization process. Weeds are unwanted wild plants and they grow in an area in competition with cultivated plants. These weeds possess invasive and vigorous nature of growth which causes threat to agriculture. The detailed study of weed colonization reveals their robust and adaptive nature to environment change. These properties of weeds have been captured in 'Invasive Weed Optimization' algorithm which makes it a powerful stochastic technique (Mehrabian and Lucas, 2006).

IWO needs initial population to start with. Therefore, the initialization process starts with the dispersion of finite number of seeds (optimized parameters) within the upper and lower limits of the search space. This causes every seed to grow to a flowering plant (solution) and depending on its fitness value (objective function value), produces seeds. This process of seed production is termed as *Reproduction*. Then the random spatial dispersion of newly produced seeds takes place over the search space. The process of reproduction and spatial dispersion continues until the number of plants reached to its maximum limit. Now the plants having lower fitness value (for minimization problem) can survive and take part in reproduction while others are eliminated. This process is called *Competitive Exclusion*. The process of reproduction and competitive exclusion continues until maximum number of iterations is reached and the plant having lowest fitness value is the optimal solution (Mehrabian and Lucas, 2006).

CHAPTER 3

THEORETICAL BACKGROUND

3.1 Optimization Algorithms

In general, global optimization techniques start with the initialization of population members within the search space. The search space is defined by the upper and lower bounds of the parameters to be optimized. Therefore, if we have N number of parameters to be optimized, the optimization problem will be of N-dimension. The optimization problem always has an objective function, which in most of the cases, needs to be minimized. Therefore the algorithm description is based on minimization problem. After population initialization, evaluation of objective function for each member of population is conducted and the solution having the least value of objective function is selected as the best solution of the current population. The next step is to create members for new generation and objective function values are evaluated for the newly generated members. These new solutions are then compared with their parents in objective function space and better solutions are moved to new generation. This process of creating new population for next generation continues till the maximum numbers of generations have been achieved.

3.1.1 Covariance-Matrix Adaptation Evolutionary Strategy (CMAES)

Covariance matrix adaptation evolutionary strategy known as CMA-ES is a stochastic method for real parameter (continuous domain) optimization of non-linear and non-convex functions. In CMAES, at each iteration g, a population of λ points is generated such that the distribution across each dimension should be normal hence forming a multivariate normal distribution. This can be achieved by obtaining a mean, standard deviation and covariance matrix of the previous iteration.

Mathematically,

Let

g = step size (belongs to natural numbers)

m^g = sequence of mean values of the multivariate normal distribution

σ^g = sequence of step size (standard deviation)

C^g = sequence of covariance matrix

Then the sampling of λ points for the new population $(x_i^g)_{i=1,\ldots,\lambda}$ can be written as

$$\boldsymbol{x_i^{g+1} = m^g + \{\sigma^g . \mathcal{N}_i(0, C^g)\}}, \qquad \boldsymbol{i = 1, \ldots, \lambda.} \qquad \textbf{……… (3.1)}$$

where

$\mathcal{N}_i(0, C^g)$ = independent multivariate normal distributions with zero mean vector and covariance matrix C^g.

After generation of new population, a new mean $m^{(g+1)}$ is calculated. It can be done by calculating weighted average of the μ selected points from the new population $x_1^{(g+1)}, \ldots, x_\lambda^{(g+1)}$

i.e.

$$\boldsymbol{m^{(g+1)} = \sum_{i=1}^{\mu} w_i x_{i:\lambda}^{(g+1)}} \qquad \textbf{……………………………... (3.2)}$$

where

$$\sum_{i=1}^{\mu} w_i = 1, \qquad w_1 \geq w_2 \geq \cdots \geq w_\mu > 0$$

$\mu \leq \lambda$ = parent population size, i.e. the number of selected points

The next step in the CMAES algorithm development is step size control. The step size control updates the standard deviation at every step. It can be given by

$$\boldsymbol{p_\sigma^{(g+1)}} = (\boldsymbol{1} - \boldsymbol{c_\sigma})\boldsymbol{p_\sigma^{(g)}} + \sqrt{\boldsymbol{c_\sigma}(\boldsymbol{2} - \boldsymbol{c_\sigma})\mu_{\boldsymbol{eff}}}\,\boldsymbol{C}^{(g)^{-\frac{1}{2}}}\frac{\boldsymbol{m}^{(g+1)} - \boldsymbol{m}^{(g)}}{\boldsymbol{\sigma}^{(g)}} \quad \text{.... (3.3)}$$

$$\boldsymbol{\sigma}^{(g+1)} = \boldsymbol{\sigma}^{(g)} \exp\left(\frac{\boldsymbol{c_\sigma}}{\boldsymbol{d_\sigma}}\left(\frac{\left\|\boldsymbol{p_\sigma^{(g+1)}}\right\|}{E\|\mathcal{N}(\boldsymbol{0},\boldsymbol{1})\|} - \boldsymbol{1}\right)\right) \quad \text{................... (3.4)}$$

The last step of the algorithm is the covariance matrix adaptation and it is explained below

$$\boldsymbol{p_c^{(g+1)}} = (\boldsymbol{1} - \boldsymbol{c_c})\boldsymbol{p_c^{(g)}} + \sqrt{\boldsymbol{c_c}(\boldsymbol{2} - \boldsymbol{c_c})\mu_{\boldsymbol{eff}}}\,\frac{\boldsymbol{m}^{(g+1)} - \boldsymbol{m}^{(g)}}{\boldsymbol{\sigma}^{(g)}}$$

$$\text{... (3.5)}$$

$$\boldsymbol{C}^{(g+1)} = \left(\boldsymbol{1} - \boldsymbol{c_1} - \boldsymbol{c}_\mu\right)\boldsymbol{C}^{(g)} + \boldsymbol{c_1}\boldsymbol{p_c^{(g+1)}}\boldsymbol{p_c^{(g+1)}}^{\boldsymbol{T}} + \boldsymbol{c}_\mu \sum_{\boldsymbol{i=1}}^{\mu} \boldsymbol{w_i}\boldsymbol{y}_{\boldsymbol{i:\lambda}}^{(g+1)}\left(\boldsymbol{y}_{\boldsymbol{i:\lambda}}^{(g+1)}\right)^{\boldsymbol{T}}$$

$$\text{... (3.6)}$$

There are some parameters which are set as default and these parameters are given by

For selection and recombination:

$$\lambda = 4 + \lfloor 3\ln(n) \rfloor$$

$$\mu = \lfloor \mu' \rfloor, \qquad \mu' = \frac{\lambda}{2}$$

$$w_i = \frac{w_i'}{\sum_{j=1}^{\mu} w_j'}, \quad w_i' = \ln(\mu' + 0.5) - \ln(i), \quad for\ i = 1, \ldots, \mu$$

For step size control:

$$\boldsymbol{c_\sigma} = \frac{\mu_{\boldsymbol{eff}} + \boldsymbol{2}}{\boldsymbol{n} + \mu_{\boldsymbol{eff}} + \boldsymbol{5}}, \quad \boldsymbol{d_\sigma} = \boldsymbol{1} + \boldsymbol{2}\,\mathbf{max}\left(\boldsymbol{0}, \sqrt{\frac{\mu_{\boldsymbol{eff}} - \boldsymbol{1}}{\boldsymbol{n} + \boldsymbol{1}}} - \boldsymbol{1}\right) + \boldsymbol{c_\sigma} \quad \text{......... (3.7)}$$

For covariance matrix adaptation:

$$c_c = \frac{4 + (\frac{\mu_{eff}}{n})}{n + 4 + (\frac{2\,\mu_{eff}}{n})}$$

$$c_1 = \frac{2}{(n + 1.3)^2 + \mu_{eff}}$$

$$\boldsymbol{c_\mu = \min\left(1 - c_1, \alpha_\mu \frac{\mu_{eff} - 2 + \left(\frac{1}{\mu_{eff}}\right)}{(n+2)^2 + \left(\frac{\alpha_\mu\,\mu_{eff}}{2}\right)}\right), \quad with\ \alpha_\mu = 2} \quad \text{.........} \ \textbf{(3.8)}$$

The global search performance is highly sensitive to the population size 'λ'. The robustness of CMAES and global search capability increases with increasing values of λ but with a reduction in convergence speed.

Figure 3.1 elucidates the CMAES algorithm.

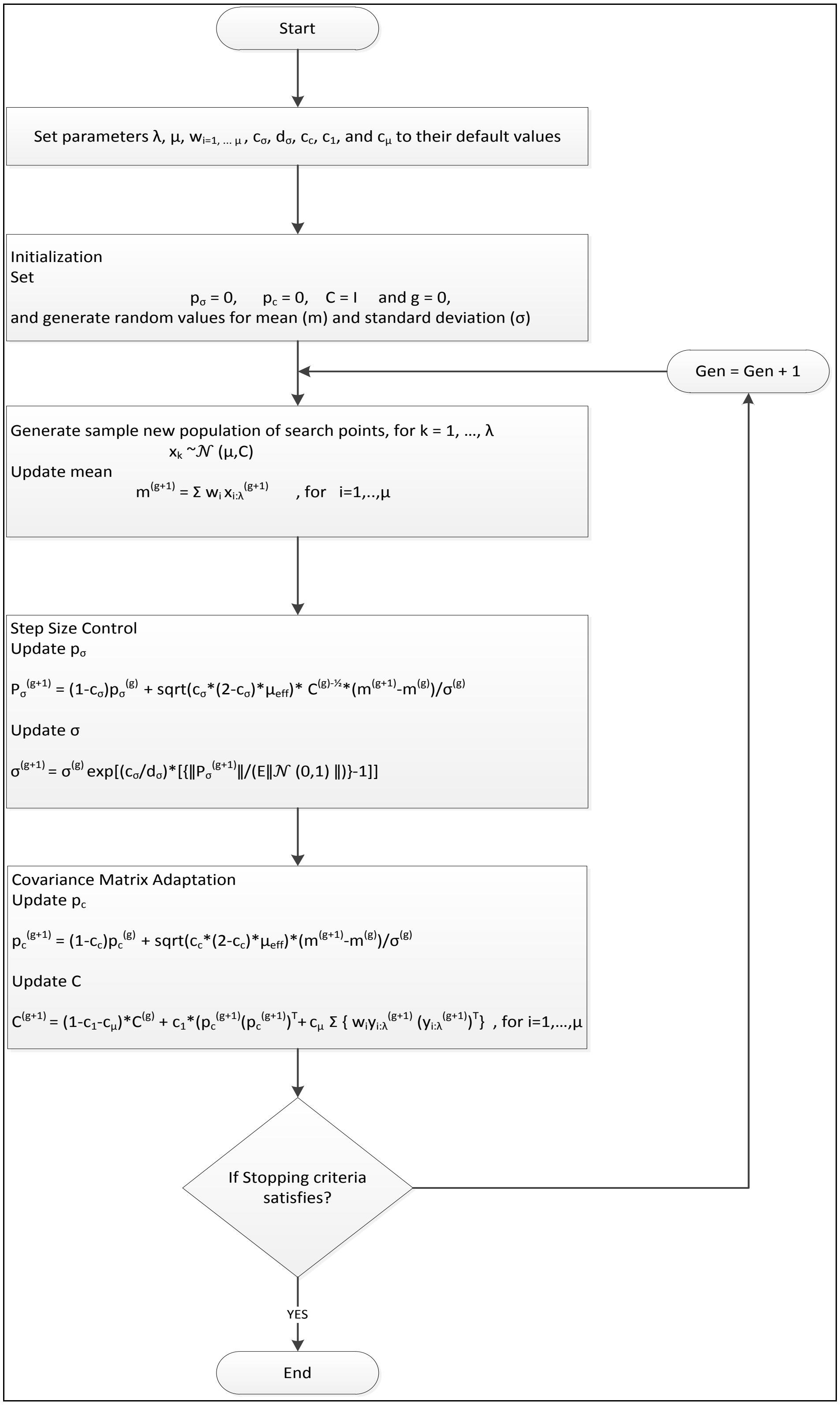


Figure 3.1: Flow chart of Covariance Matrix Adaptation Evolutionary Strategy (CMAES)

3.1.2 Differential Evolution

During 1994 and 1996, Kenneth Price and Rainer Storn proposed a global optimization technique called Differential Evolution. It was Price who started to work on 'Chebyshev Polynomial fitting problem' by solving it using vector differences for vector population perturbation. Their efforts ended up in the formulation of a technique known as Differential Evolution. Since then, many researchers got attracted by this algorithm and it has been widely used in solving a variety of engineering problems, e.g. non-linear programming, non-differentiable problems, function minimization and complex simulations (Storn and Price, 1995; Storn, 1995; Storn and Price, 1996; Storn, 1996a; Storn, 1996b; Lampinen and Zelinka, 1999; Lampinen, 2001, Karaboga and Okdem, 2003)

3.1.2.1 Initialization

- Problem dimensions (D) should be defined at the start of the solution. It depends upon the number of parameters to be optimized. The individual range of the parameters is very important as the optimization technique will search for the optimum solution within this prescribed range.
- The constraints used to guide the global optimization.
- Population size (N_p)
- Number of generations (G)
- Number of iterations (i)
- Mutation factor (F)
- Crossover factor (CR)

DE starts with the generation of ‘N_p’ vectors (candidate solution in the population). Each solution is composed of ‘D’ number of control variables (unknown parameters). This can be done by randomly assigning values for each parameter ‘x_i’ within its range.

$$\boldsymbol{x_{i,j} = x_{j_{min}} + random \,\#\, (x_{j_{max}} - x_{j_{min}})} \qquad \text{..................} \textbf{(3.9)}$$

where

i = 1,j = 1 : D

3.1.2.2 Evaluation and Finding the best solution

The objective function value for each solution (vector) is evaluated and compared to get the best solution of the generation. The global best solution is stored externally and updated after every generation.

3.1.2.3 Mutation

Mutation is the first step towards generation of new solutions. In this operation, a mutant vector is generated for every solution in the initial population using one of the following formulas

$$\boldsymbol{V_i^{(G+1)} = X_{r1}^{(G)} + F(X_{r2}^{(G)} - X_{r3}^{(G)})} \qquad \text{..........................} \textbf{(3.10)}$$

$$\boldsymbol{V_i^{(G+1)} = X_{best}^{(G)} + F\left(X_{r1}^{(G)} - X_{r2}^{(G)}\right)} \qquad \text{..........................} \textbf{(3.11)}$$

$$\boldsymbol{V_i^{(G+1)} = X_i^{(G)} + F\left(X_{best}^{(G)} - X_i^{(G)}\right) + F\left(X_{r1}^{(G)} - X_{r2}^{(G)}\right)} \qquad \text{..................} \textbf{(3.12)}$$

$$\boldsymbol{V_i^{(G+1)} = X_{r1}^{(G)} + F\left(X_{r2}^{(G)} - X_{r3}^{(G)}\right) + F\left(X_{r4}^{(G)} - X_{r5}^{(G)}\right)} \qquad \text{..................} \textbf{(3.13)}$$

where

$X_{r1}^{(G)}, X_{r2}^{(G)}, X_{r3}^{(G)}, X_{r4}^{(G)}, X_{r5}^{(G)}$ are randomnly selected solution vectors from the current generation (different from each other and from the corresponding X_i)

$X_{best}^{(G)}$ = Solution achieving best value

F = Mutant constant having values between 0 and 1

The factor F plays a role in controlling the speed of convergence.

3.1.2.4 Crossover

Crossover operation is employed to further perturb the generated solutions and enhance the diversity. In crossover operation, the mutant vector (generated in mutation) and its corresponding initial vector (parent) in the original population are copied to a new vector named as trial vector. This is done by considering a certain crossover factor CR having a range of [1, 0] defined by the user. A random number in the range of [1, 0] is generated for each parameter in the solution and compared with the CR. If the random number generated is less than or equal to CR, then the parameter for this trial vector is selected from mutant vector otherwise it will be taken from parent vector. In case, CR is set equal to zero, then all the parameters for trail vector are taken from parent vector except one randomly selected value of trial vector is set equal to the corresponding parameter in the mutant vector. However, if CR is defined as 1, then all the parameters for trail vector are taken from mutant vector except one randomly selected value of trial vector is set equal to the corresponding parameter in the parent vector.

CR plays an important role in controlling the smoothness of the convergence. Small value of CR causes the trial solutions to have the characteristics of their parent vectors and hence, slow in convergence.

3.1.2.5 Selection

Selection is the last step in the generation of a new population. In the selection process, the objective function values are evaluated for each entry of trial vector and then compared with the corresponding objective function value of the parent vector in the old generation. If the fitness of the trial vector is better than that of its parent vector, the parent is replaced with the trial vector.

3.1.2.6 Stopping Criteria

After every generation, DE calculates the global best solution and updates it. Usually maximum number of generation is set to be as the stopping criteria. However, user can examine the change in global best solution values and if the change is within the tolerance limit, then it can be selected as stopping criteria.

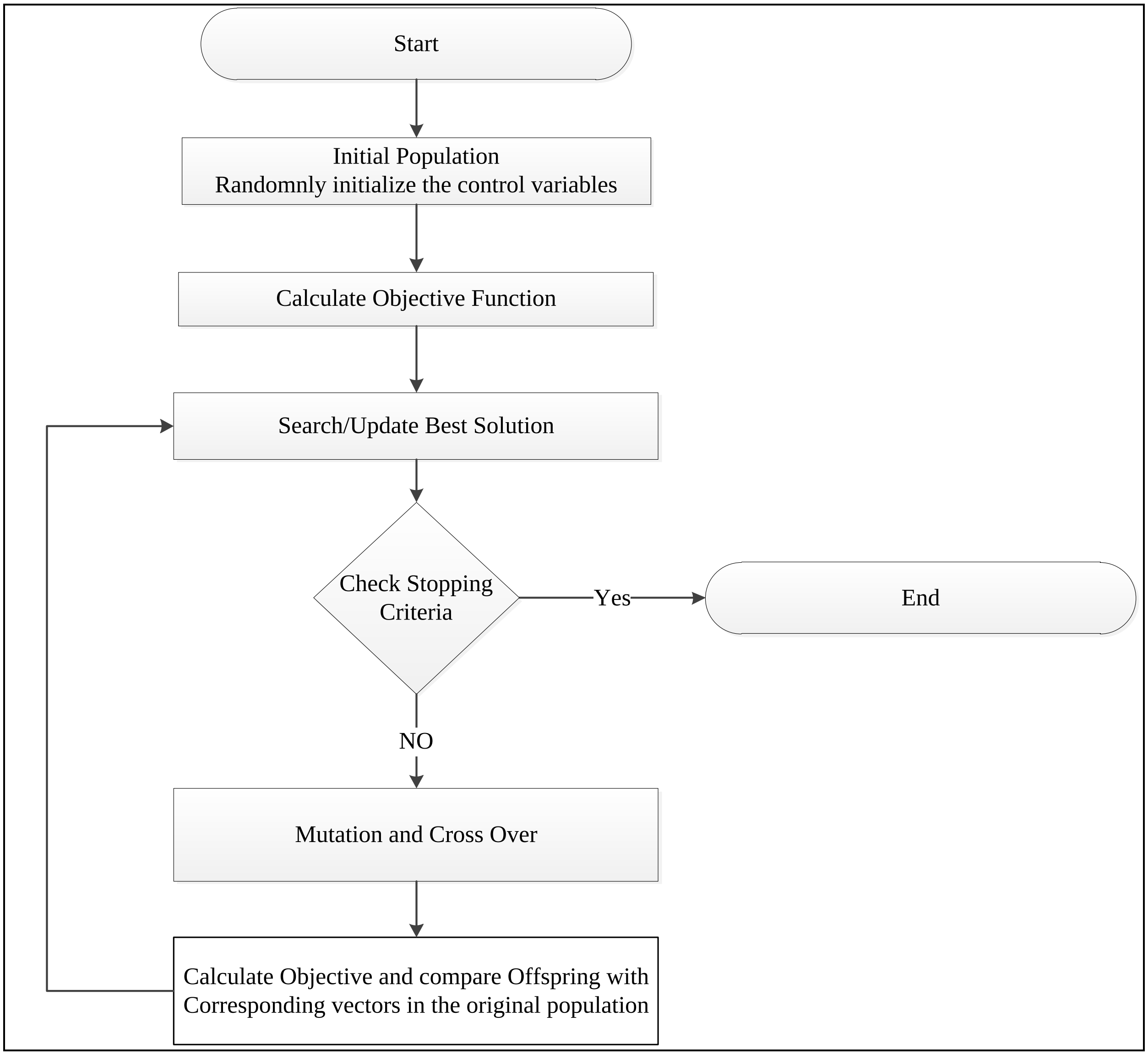


Figure 3.2: Flow chart of Differential Evolution Algorithm

3.1.3 Invasive Weed Optimization (IWO)

In 2006, A.R. Mehrabian and C. Lucas introduced a numerical evolutionary algorithm named as Invasive Weed Optimization (IWO). IWO technique is inspired by the common phenomena of colonization of invasive weeds. This phenomenon occurs in agriculture where the unwanted plants termed as weed grow naturally. The term weed refers to any unwanted plant whose vigorous and invasive growth is a threat for cultivated plants. The process description of invasive weed optimization is described here under.

3.1.3.1 Initialization

The initialization takes place with the generation and random dispersion of finite number of seeds in the d dimensional problem space. These seeds forms the initial population of the optimization problem.

3.1.3.2 Reproduction

The process of growth of an individual seed to a flowering plant is termed as reproduction. However, the capability of seed production of individual flowering plant depends upon the fitness of the plant and the colony’s lowest and highest fitness values. The seed production capability of each plant in the colony varies linearly from minimum possible seed production to maximum value. The production of seed from individual plant depends upon the fitness value of plant in the colony. It means that a plant will produce seeds based on its fitness, the colony's lowest fitness and highest fitness to make sure the increase is linear. Fig. 3.3 illustrates the procedure:

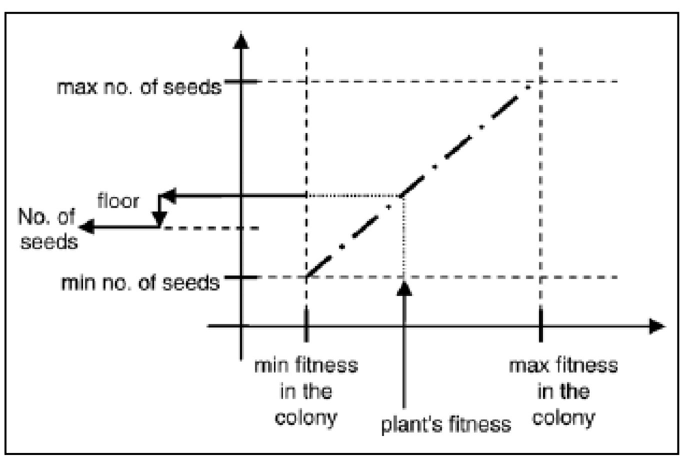


Figure 3.3: Seed production procedure in a colony of weeds.

The reproduction step in IWO is somehow different than that in other evolutionary algorithms which adds an significant property to the search algorithm. The usual trend in evolutionary algorithms for the selection of feasible solution is to select the ones who have better fitness values than the infeasible solution (solutions having low fitness values). Here "better" means to have more chance to survive and reproduce. Due to this selection criteria, the infeasible solutions are not allowed to take part in the reproduction process. However, there exists a possibility that some infeasible solutions may carry useful information and lead to a better solution after evolution process. Furthermore, the optimal point can be achieved more easily if the system is allowed to "cross" an infeasible region (especially in non-convex feasible search space). Therefore, IWO allows the feasible and infeasible solutions, both, to take part in evolutionary process similar to the mechanism happens in nature.

3.1.3.3Spatial Dispersal

Spatial dispersion provides the randomness and adaptation to the search algorithm. In this section, the produced seeds are randomly dispersed in the search area and are allowed to grow to new plants.

$$\begin{aligned}&\boldsymbol{Solution} = \\ &\boldsymbol{Mean} + (\boldsymbol{Standard\ Deviation}\ \times \\ &\boldsymbol{Normally\ distributed\ random\ number})\end{aligned} \quad \text{.. (3.14)}$$

$$\begin{aligned}&\boldsymbol{New\ plant} = \\ &\boldsymbol{Old\ Plant} + (\ \boldsymbol{\sigma_{iter}}\ \times\ \boldsymbol{Normally\ distributed\ random\ number})\end{aligned} \quad \text{...................... (3.15)}$$

Where σ_{iter} is the standard deviation of the current generation.

The spatial dispersion allows new plants to produce their seeds (based on their fitness value) and disperse in their own vicinity which is controlled by the calculated value of standard deviation for that particular generation. However, standard deviation (SD), σ, of the random function will be reduced from a previously defined initial value, $\sigma_{initial}$, to a final value, σ_{final}, in every step (generation).

$$\boldsymbol{\sigma_{iter}} = \frac{(iter_{max} - iter)^n}{(iter_{max})^n}\left(\boldsymbol{\sigma_{initial}} - \boldsymbol{\sigma_{final}}\right) + \boldsymbol{\sigma_{final}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.16)}$$

3.1.3.4Competitive Exclusion

Competitive exclusion compares the number of plants in the colony with the maximum number of plants allowed. The process of spatial dispersion of the seeds in the colony continues until maximum number of plants in the colony is reached. Then, only those plants are allowed to survive and produce which have lower (for minimization problem) / higher (for maximization problem) fitness value. The process of competitive exclusion continues until maximum iterations is reached and the solution having the best fitness value is selected as the optimal solution.

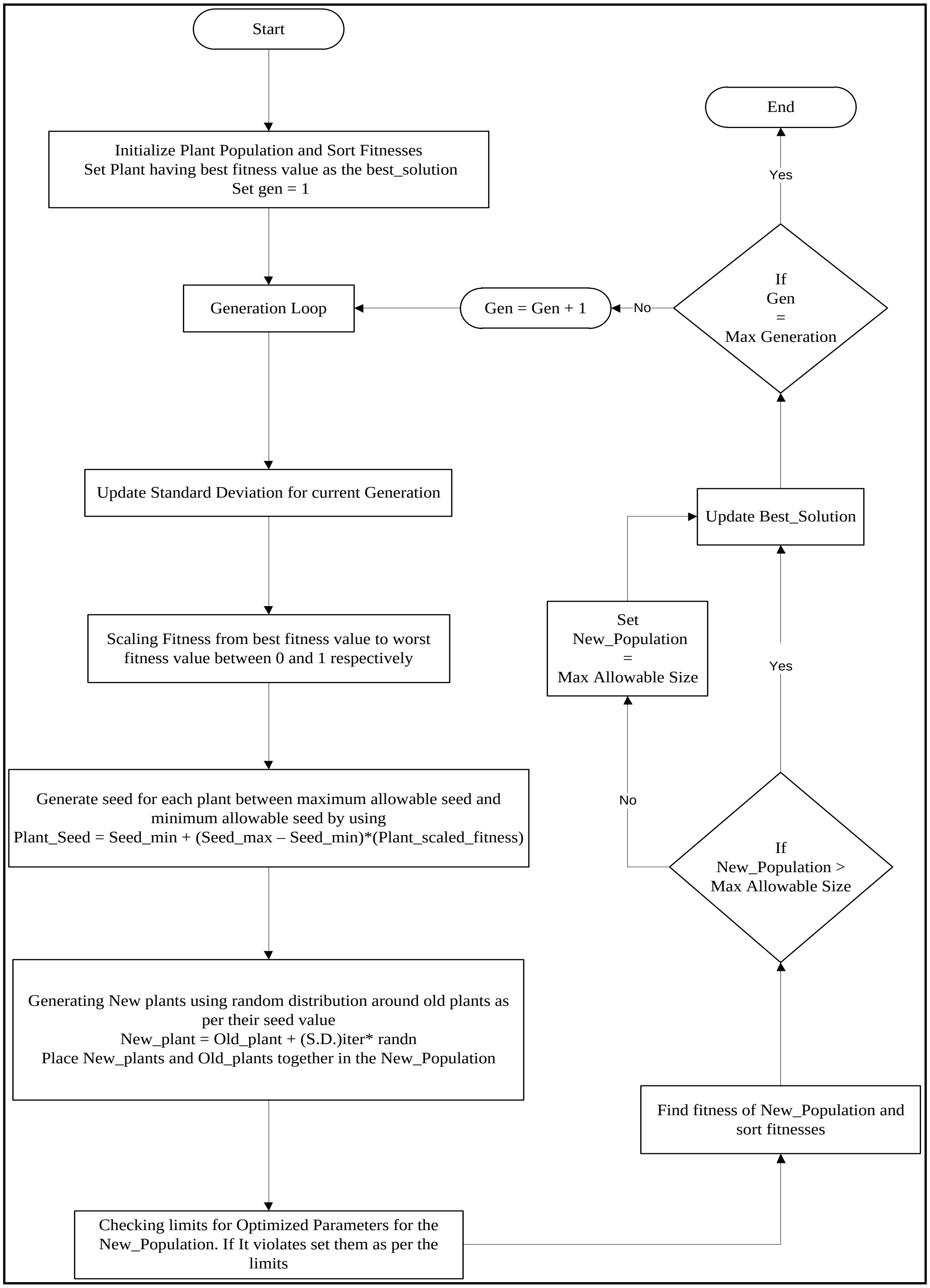


Figure 3.4: Flow chart of Invasive Weed Optimization Algorithm

CHAPTER 4

STATEMENT OF THE PROBLEM

It is evident from the literature review that up to recent times, most sensitivity studies have been done manually. Quality maps were also employed for the optimization of some flooding processes. However stochastic optimization algorithms have shown promising results in optimizing engineering problems. Therefore the fact that there is a large number of parameters to be optimized in SP flooding makes stochastic optimization algorithms a suitable candidate for process optimization.

Stochastic optimization techniques have been used for the optimization of polymer flooding and surfactant flooding using various optimized parameters. However, a comprehensive evaluation of surfactant-polymer flooding needs to be done to come up with the effect of all the variables involved in the process on net present value (NPV) and ultimate recovery (UR) which are the guiding objectives of the EOR process. Furthermore, the current techniques, such as Genetic algorithm, Polytope algorithm, etc, used for optimization of SP flooding are not time efficient and requires greater computational capabilities. Hence selecting appropriate optimization technique becomes important.

4.1 Research Objectives

The research objectives are:

1. To study performance of three recent evolutionary optimization algorithms namely Covariance Matrix Adaptation Evolutionary Strategy (CMAES), Differential Evolution (DE) and Invasive Weed Optimization (IWO) in estimating the design variables in a surfactant-polymer flooding.
2. To come up with recommendation on the best algorithm for the design of surfactant-polymer flooding.

4.2 Reservoir Model

This research uses heterogeneous reservoir with vertical and horizontal heterogeneity. The polymer solution is represented in the model as miscible in the aqueous phase and shows no influence on the flow of hydrocarbon phases. Therefore, standard black oil equation is used for the flow of hydrocarbon phases in the model. The water and polymer equations are presented hereunder (Schlumberger, Eclipse Technical Description Manual, 2010).

$$\boldsymbol{\frac{V_b}{\Delta t}\Delta_t\left(\frac{\emptyset S_w}{B_r B_w}\right) = \sum\left[\frac{T_{w_{m,m'}}}{R_k}\left(P_{w_{m'}} - P_{w_m}\right) - \rho_w g(z_{m'} - z_m)\right] + Q_w} \quad \text{.........(4.1)}$$

$$\boldsymbol{\frac{1}{\Delta t}\Delta_t\left(\frac{V^* S_w C_p}{B_r B_w}\right) + \frac{1}{\Delta t}\Delta_t\left(V\rho_r C_p^a \frac{1-\phi}{\phi}\right) = \sum\left[\frac{T_{w_{m,m'}}}{R_k}\left(P_{w_{m'}} - P_{w_m}\right) - \rho_w g(z_{m'} - z_m)\right] C_p + Q_w C_p} \quad \text{.........(4.2)}$$

$$\boldsymbol{V^* = V_b \emptyset\left(1 - \frac{S_{dpv}}{S_w}\right).} \quad \text{.........(4.3)}$$

Where

$T_{w_{m,m'}}$ = Transmissibility of cell 'm' and its neighboring cells = $\frac{k_{rw}}{B_w \mu_{p_{eff}}}\left(\frac{KA}{\Delta x}\right)_{m,m'}$

S_{dpv} = Dead pore space within each grid cell

C_p^a = Polymer adsorption concentration

ρ_r = Mass density of the rock formation

ϕ = Porosity

ρ_w = Water density

Σ = Sum over neighboring cells

R_k = Relative permeability reduction factor due to aqueous phase due to polymer retension

C_p = Polymer concentration in the aqueous phase

$\mu_{w_{eff}}$ = Effective viscosity of water

$\mu_{p_{eff}}$ = Effective viscosity of polymer

D_z = Cell center depth

B_r, B_w = Rock and water formation volumes

T = Transmissibility

k_{rw} = Water relative permeability

S_w = Water saturation

V_b = Block bulk volume

$\emptyset$ = Block porosity

Q_w = Water production rate

P_w = Water pressure

g = Gravity acceleration

Similar to polymer, surfactant is also assumed to exist in water phase only and distribution of injected surfactant can be modeled by solving a conservation equation for surfactant within water phase.

4.3 Optimized Parameters

The design parameters in the optimization problem considered are polymer concentration, surfactant concentration, well locations and injection profiles.

4.3.1 Polymer Concentration

Polymer is used to control the mobility of injected water especially in high permeability layers where water can quickly breakthrough as compared to other layers. Polymer increases the viscosity of water and hence reduces water relative permeability. It has been confirmed experimentally that the higher the polymer concentration, the higher will be the overall viscosity of the injected water and hence increasing the sweep efficiency which in turn increases the oil recovery (Fig. 4.1 and Fig.4.2). However, increased water viscosity causes high injection pressure at a constant injection rate. If the pressure is too high, the reservoir rock will tend to fracture. Moreover, the optimal value of polymer viscosity, and hence the concentration, is not the maximum value which opposes the conventional belief regarding it. Therefore, an optimum value of polymer concentration is needed for safe and efficient design of SP flooding process (Hongjiang Lu, 2004; Wang et al., 2010). Thus, we include polymer concentration as one of the design variable in SP flooding.

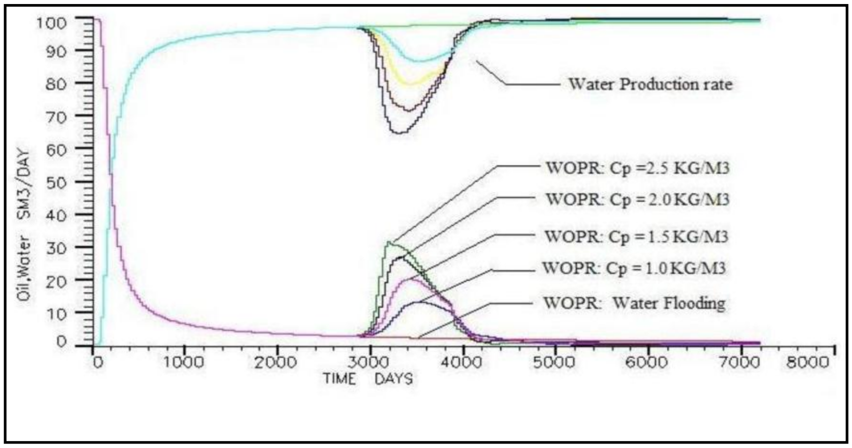


Figure 4.1: Oil and water production rates with different polymer concentrations (Hongjiang Lu, 2004)

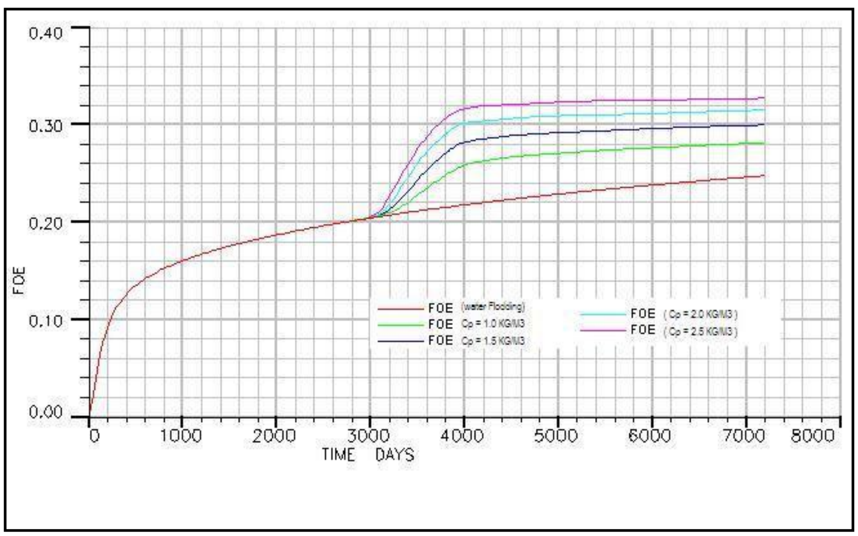


Figure 4.2: Oil recovery with different polymer concentrations (Hongjiang Lu, 2004)

4.3.2 Surfactant Concentration

Reduction of interfacial tension (IFT) is an important phenomenon for enhanced oil recovery. Surfactants are used to reduce the interfacial tension between two immiscible liquids. Surfactant is a substance that when present in a low concentration in a system, has the property to orient itself at the interfaces of two liquids in such a way that it alters the IFT between the contacting liquids (Rosen, 1989). However the reduction in IFT strongly depends upon the concentration of surfactant present in the SP flood. Surfactants having the lowest IFT values are preferred for SP flooding. At ultra low values of IFT the capillary number increases to 10^{-2} and irreducible oil saturation approaches zero for homogeneous reservoirs (Chatzis et al., 1984). This reduction is IFT allows the displacing fluid to displace the oil from the pores and hence increases the displacement efficiency. Since the oil recovery is the product of displacement and sweep efficiency, the SP flood should be designed such that the overall effect of sweep efficiency and displacement efficiency is towards maximum oil recovery. Hence the optimal value of IFT for surfactant is not the lowest value of IFT. Since IFT reduction is related to surfactant concentration, therefore surfactant concentration is considered as one of the optimized parameters.

4.3.3 Well Placement

After the development of geological model, placement of injection and production wells is one of the most critical steps in the field development process. Well placement includes determination of optimum number of wells, their type and location in the reservoir. The optimization of these parameters is required for efficient and economical hydrocarbon production from the reservoir. Researchers found non-gradient based optimization techniques as an efficient tool for well placement optimization (Bittencourt and Horne, 1997; Yeten et al., 2002; Ozdogen and Horne, 2006; Bangerth et al., 2006; Emerick et al., 2009). In recent times, these optimization techniques have been improved resulting in more efficient estimation of the proper placement of wells in a reservoir (Handels et al., 2007; Sarma and Chen, 2008; Wang et al., 2007; Zhang et al., 2010). Therefore, this study addresses the optimization of vertical wells in horizontal plane using three recently developed stochastic optimization algorithms.

4.3.4 Injection profiles

Injection of surfactant and polymer in the reservoir changes its rock-fluid interaction behavior. However for an effective and economical SP flooding process, the time duration of surfactant and polymer injection should be estimated. In field application, the surfactant and polymer injection periods are shorter due to the cost of these chemicals with respect to oil price (Nawaf and Mamora, 2011). Therefore, injection profile during tertiary recovery needs to be selected as a parameter to be optimized.

The production life of the reservoir depends upon the constraints imposed during the production. If the conditions during production are unable to meet these constraints, the reservoir is considered as uneconomical and hence abandoned. Some factors that affect the flooding process are the relative duration of water, surfactant and polymer flooding. Therefore, these parameters should be optimized in an SP flood.

4.4 Objective Function

Objective function is a measure of performance of different alternative scenarios in a project. It measures how good different combinations of design variables are.

We consider two objective functions: the net present value (NPV) and the ultimate recovery (UR) of the SP flood project.

4.4.1 Net Present Value (NPV)

A project can be classified as successful or unsuccessful based on its net present value. Thus, NPV is a measure of a project’s success and for this research, it is an economic indicator for the field development. Therefore, we optimize the design parameters based on the NPV of different candidate solutions. NPV can be positive or negative. A positive value indicates a net financial profit while a negative value indicates a net financial loss of the project (Mian, 2002a).

The economic analysis includes oil price, operating cost including produced water handling and water/surfactant/polymer injection, discount rate and chemical costs as the most important economic variables.

The net present value can be calculated as

$$\boldsymbol{NPV} = \sum_{i=1}^{N} \frac{\left(\boldsymbol{OPR}.\$_{oil} - \boldsymbol{W}_{prod}.\$_{water\ prod} - \boldsymbol{W}_{inj}.\$_{water\ inj} - \boldsymbol{Chem}.\$_{chemical}\right)_i.\Delta t_i}{(1+r)^{t_i}} \quad \text{……….……. (4.4)}$$

Where,

OPR = Field oil production rate (STB/time step)

W_{prod} = Field water production rate (STB/time step)

W_{inj} = Field water injection rate (STB/time step)

Chem = Field chemical (surfactant + polymer) injection rate (lbs/bbl)

$\$_{oil}$ = Price of oil (\$/STB)

$\$_{water\ prod}$ = Cost of handling produced water (\$/STB)

$\$_{water\ inj}$ = Cost of water injection (\$/STB)

$\$_{chemical}$ = Cost of chemical (\$/lb)

i = time step counter

t_i = time value for i^{th} time step

Δt_i = time interval for i^{th} time step

r = discount rate (%)

4.4.2 Ultimate Recovery Factor (URF)

Surfactant-Polymer flooding process involves the injection of surfactant solution followed by polymer solution and chase water. The design of SP flooding is such that the surfactant alters the wettability by adsorption on the rock surface. It causes the reduction in residual oil saturation which results in improved recovery. Thus, the recovery factor before and after the SP-flooding is not the same. For an efficient flooding process, the recovery factor is one of the parameters to be considered. Hence, the injection of surfactant should be designed considering the original wetting phase (Najafabadi et al., 2008) such that it yields high recovery factor.

$$\textit{Recovery Factor} = \frac{\textit{Cumulative Oil Produced}}{\textit{Original Oil in Place (OOIP)}} \qquad \text{………………. (4.5)}$$

CHAPTER 5

RESULTS AND DISCUSSIONS

Surfactant-Polymer flooding process was considered as one of the expensive enhanced oil recovery (EOR) method despite its effectiveness in improving ultimate recovery. The impression of SP flooding to be an expensive EOR process, attracted the attention of the researchers towards the optimization of this process. Several attempts have been made in this regard in the last two decades and a number of sensitivity studies have been performed for polymer concentration (Wu et al., 1996; Dang et al., 2011; Shehata et al., 2012), surfactant concentration (Jakobsen and Hovland, 1994; Wu et al., 1996; Dang et al., 2011; Xu et al., 2011), polymer viscosity (Wang et al., 2010; Seright, 2010; Levitt et al., 2011; Shehata et al., 2012), surfactant interfacial tension (Wang et al., 2010; Nawaf and Mamora, 2011), polymer adsorption (Zheng et al., 2000; Dang et al., 2011; Doren et al., 2011), surfactant adsorption (Krumrine et al., 1982; Curbelo et al., 2005; Dang et al., 2011), rock wettability (Nawaf and Mamora, 2011; Dang et al., 2011) and time duration of SP flooding (Nawaf and Mamora, 2011) to name a few. However, these sensitivity studies were limited to a few set of values for each optimized parameter.

Well placement on the other hand, is one of the most important steps in the field development process. The placement of the wells in the reservoir is a strong function of reservoir heterogeneity and geological properties. If properly selected, an optimized well placement in the reservoir can bring remarkable increase in the net present value (NPV) and help in increasing ultimate recovery from the reservoir. This research proves the interdependency of the water-flooding, SP flooding and well placement from both the ultimate recovery and the economic point of view.

The advancement in stochastic evolutionary algorithms makes it possible to search for the global optimize set to parameters for various engineering problems. The implementation of different stochastic evolutionary algorithms requires understanding the behavior of the problem and selecting a suitable evolutionary algorithm for that particular problem.

This research presents a comprehensive optimization of surfactant-polymer flooding with well placement. The time for initial water-flooding, time for surfactant flooding, time for polymer flooding, injection and production well locations, surfactant and polymer concentration in injection wells during surfactant and polymer flooding respectively are used as the parameters to be optimized.

5.1 Reservoir Simulation Model Description

Numerical reservoir simulators can predict the complex EOR mechanism with some limitations. However improved reservoir simulators are in the stage of development as new methods of EOR are on the verge of implementation. In this research, two synthetic reservoir models were used for the optimization problem.

1. Reservoir Model 1 : Channel Reservoir with Four Facies
2. Reservoir Model 2 : Heterogeneous Reservoir with Fully Distributed Permeability Field

The reservoir models' details are mentioned in the following subsections

5.1.1 Reservoir Model 1: Channel Reservoir

Model 1 is a three layer channel reservoir composed of four facies. The petrophysical properties of individual facies are given in Table 5.1.

Table 5.1: Petrophysical Properties of Individual Facies for Reservoir Model 1

Facies	Porosity (%)	Permeability (md)
0	13	100
1	27	2500
2	22	700
3	7	5

The reservoir is of dimension 6000 ft x 6000 ft x 150 ft. The reservoir is divided into 30 x 30 x 3 grid blocks and is attached to the edge water aquifer with productivity index of 120 bbl/day/psi. The reservoir has a top depth of 5000 ft. Figures 5.1 to 5.3 show the reservoir model for Layer 1, Layer 2 and Layer 3 respectively.

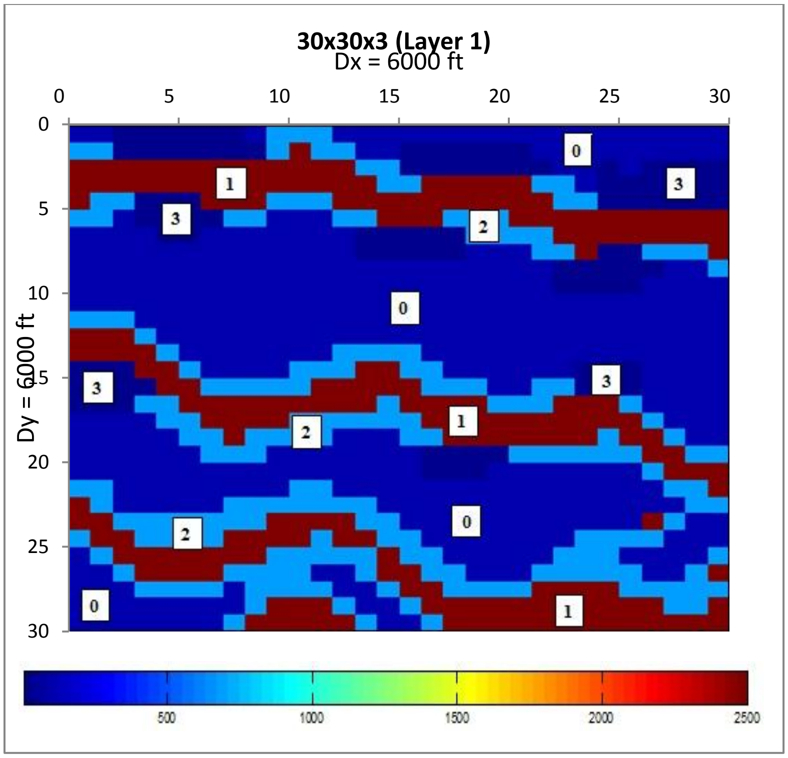


Figure 5.1: Reservoir Model 1 : Layer 1 of the Channel Reservoir

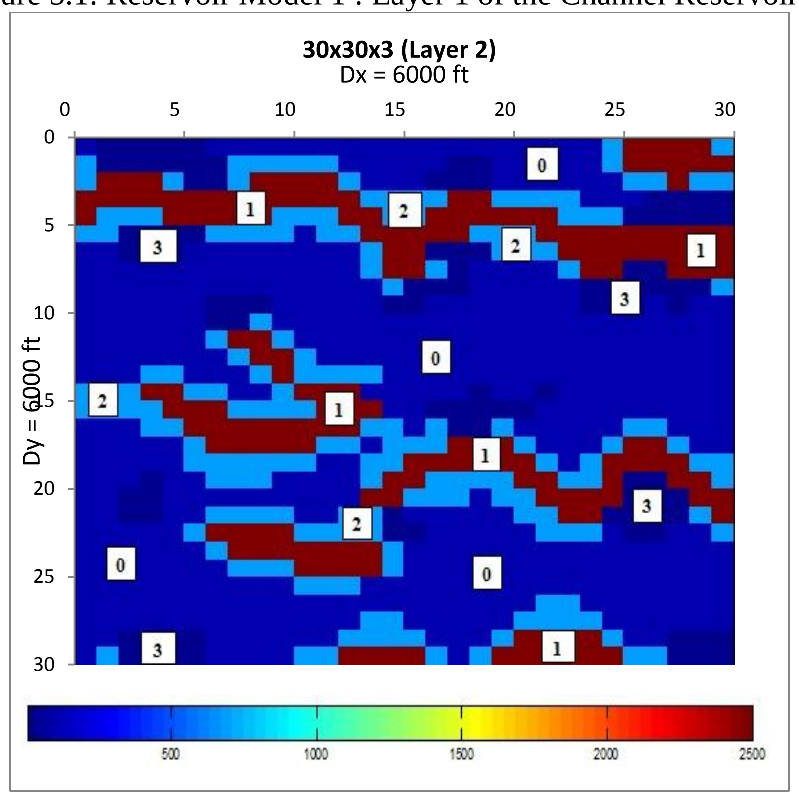


Figure 5.2: Reservoir Model 1 : Layer 2 of the Channel Reservoir

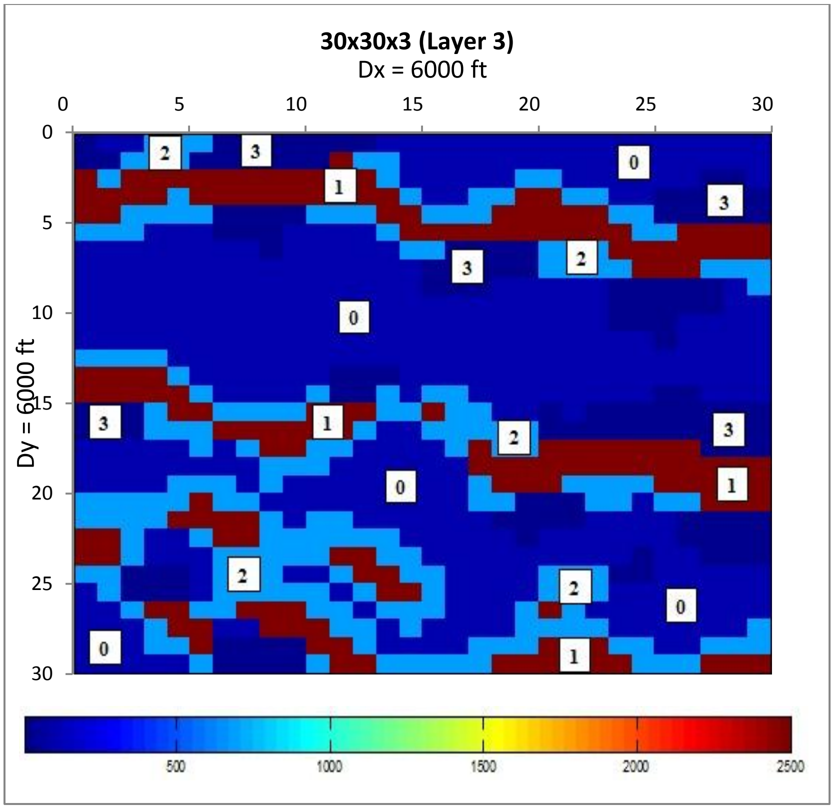


Figure 5.3: Reservoir Model 1 : Layer 3 of the Channel Reservoir

5.1.2 Reservoir Model 2 : Heterogeneous Reservoir With Fully Distributed Permeability Field

Two layer fully heterogeneous reservoir model is generated with permeability ranges from 10 md to 3000 md. The reservoir is of dimension 10000 ft x 10000 ft x 100 ft. The reservoir is divided into 50 x 50 x 2 grid blocks and is attached to the edge water aquifer with productivity index of 35 bbl/day/psi. The reservoir has a top depth of 5000ft with porosity values of 0.21 and 0.13 for Layer 1 and Layer 2 respectively. Figures 5.4 and 5.5 present the reservoir model for Layer 1 and Layer 2 respectively.

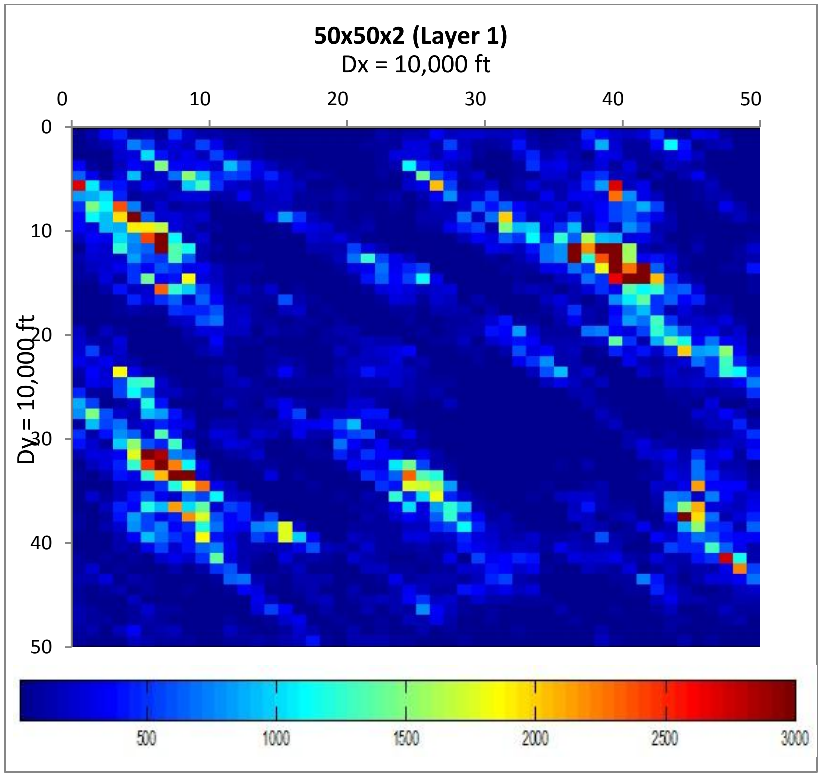


Figure 5.4: Reservoir Model 2 : Layer 1 of Heterogeneous Reservoir With Fully Distributed Permeability field

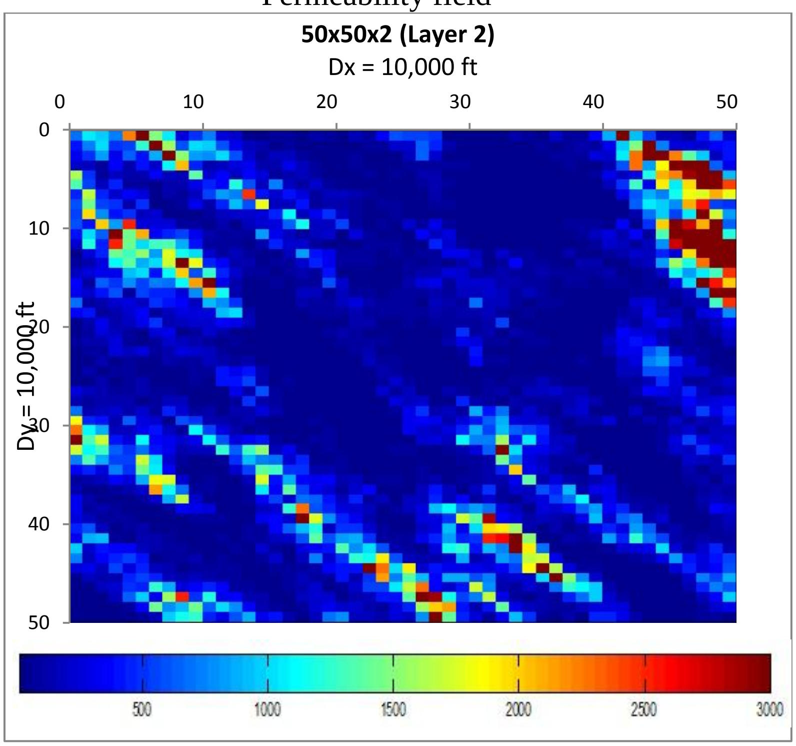


Figure 5.5: Reservoir Model 2 : Layer 2 of Heterogeneous Reservoir With Fully Distributed Permeability field

5.2 Well Controls

Eclipse reservoir simulator was used for the simulation of SP flooding. The reservoir simulator used has comprehensive options for control of individual wells as well as group of wells. Separate well controls were defined for producers and injectors depending upon the production requirements. The well controls for Reservoir Model 1 and Model 2 are the same. The controls are described in the following subsections.

5.2.1 Production Well Controls

For production wells, following controls are set

- Liquid Rate

  Liquid rate of 2000 stb/day is set as the primary constraint in each producer. The well will produced at this rate as long as the secondary control is not violated.

- Bottomhole Pressure

  Bottomhole pressure of 2000 psi is set as the minimum bottomhole pressure of individual well.

5.2.2 Injection Well Controls

The following controls are set in each injector

- Injection Rate

  Injection rate of 2000 stb/day is set as the maximum injection rate for individual injector.

- Bottomhole Pressure

  Bottomhole pressure of 6500 psi is set as the primary constraint in each injector.

5.3 Economic Limit

5.3.1 Well Economic Limit

- Oil Rate

  Oil rate of 100 stb/day is set as the minimum oil rate for individual production well. Violation of this constraint will cause the particular well to be shut-in.

- Water Cut

  Water cut of 95% is set as the maximum allowable water cut from each production well. Violation of this constraint would cause the particular well to be shut-in.

5.3.2 Group Economic Limit

- Oil Rate

  Oil rate of 100 stb/day is set as the minimum cumulative oil rate from all the production wells.

- Water Cut

  Water cut of 95% is set as the maximum allowable cumulative watercut from all the production wells. Violation of this constraint would cause the worst offending connection in the worst offending well to be shut-in.

  All injectors and producers are in one single group. At the violation of the group constraints, all wells in the group will be shut-in and simulation will be stopped. The time at which the simulation is stopped is the life cycle of the reservoir for that particular combination of well configuration and SP flood parameters. We note that different combinations of optimization parameters will reach economic limit at different times and hence the life cycle of the reservoir for each of these combinations would be different.

5.4 Reservoir Fluid Properties

The fluid and fluid-rock properties are shown in Table 5.2 and Figs. 5.6 to 5.12.

Table 5.2: Reservoir Fluid Properties

Parameters	**Value**
Initial Pressure (psia)	4000
Water Compressibility (psi^{-1})	3.13E-06
Water Viscosity (cP)	0.31
Water FVF (RB/STB)	1.029

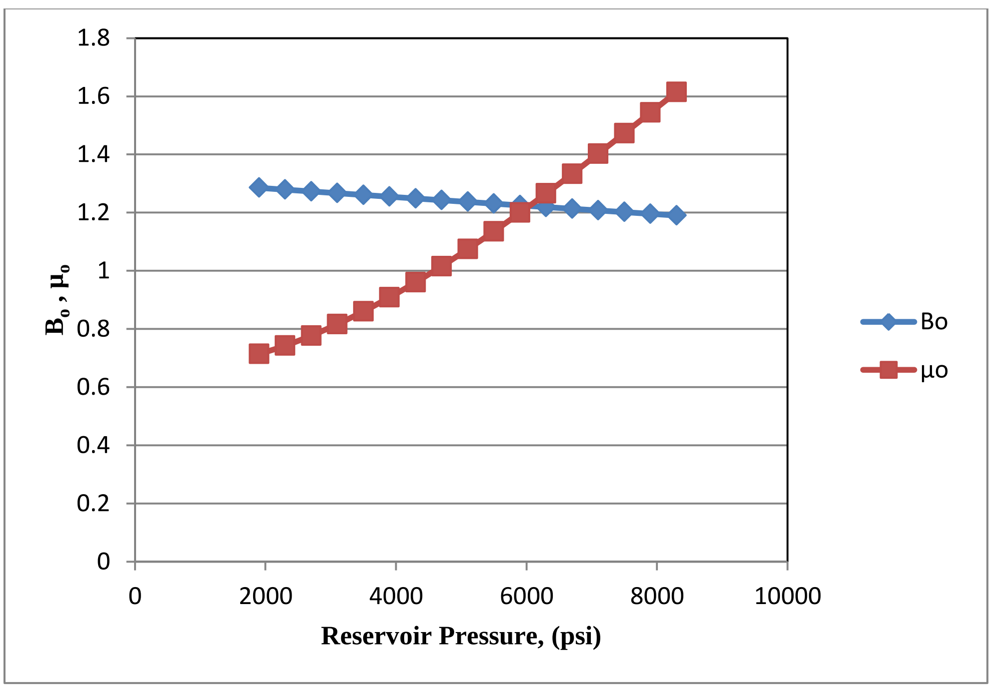


Figure 5.6: Reservoir Pressure v/s Oil Formation Volume Factor & Oil Viscosity

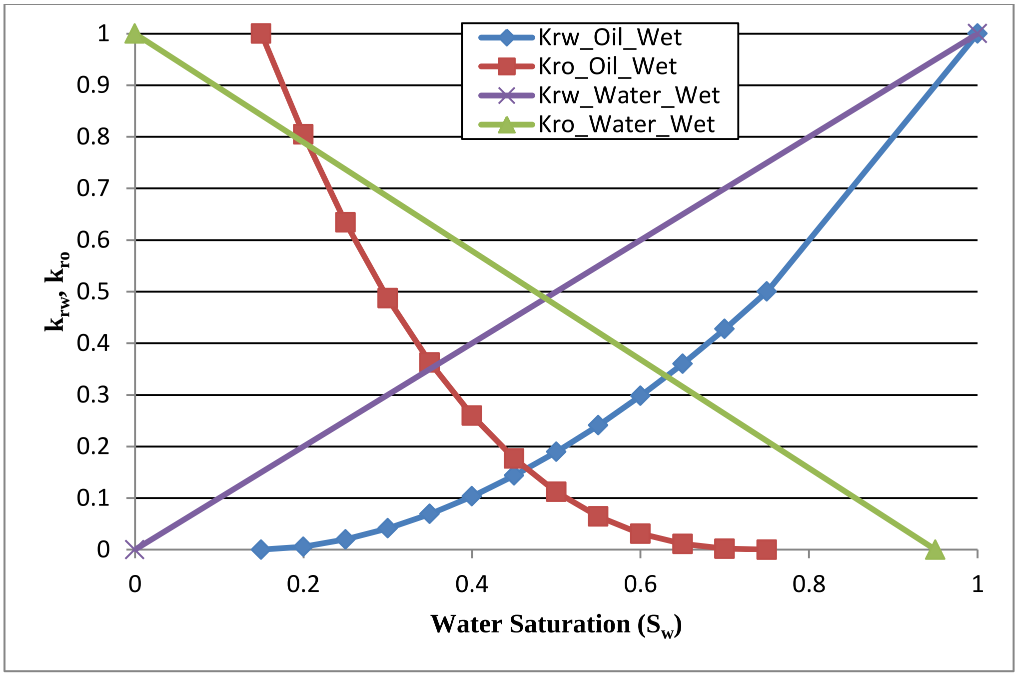


Figure 5.7: Water Saturation v/s Oil & Water Relative Permeability

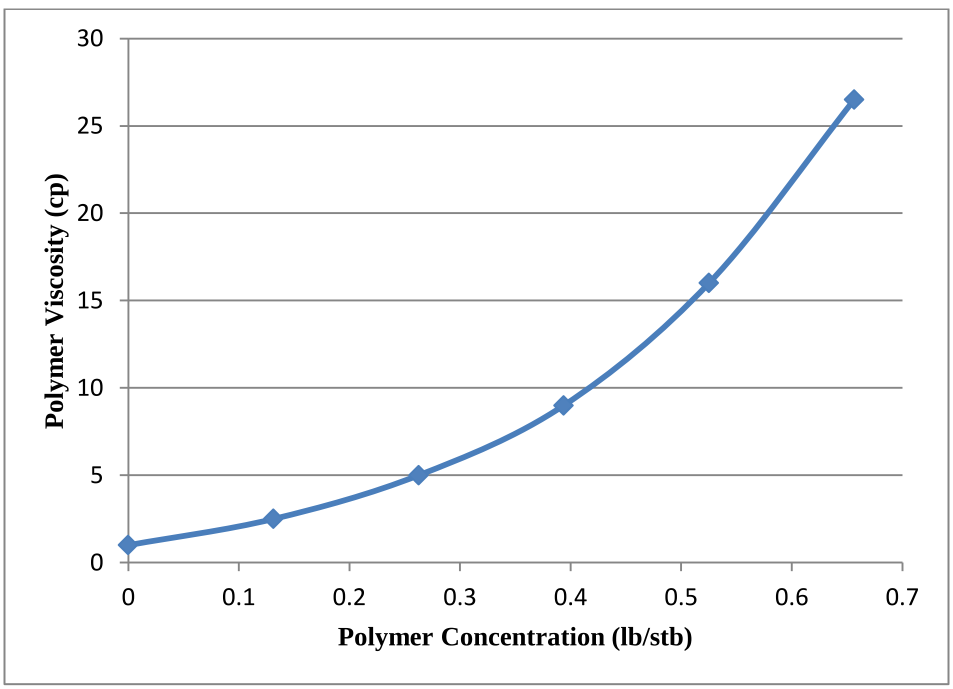


Figure 5.8: Polymer Conc. v/s Polymer Viscosity

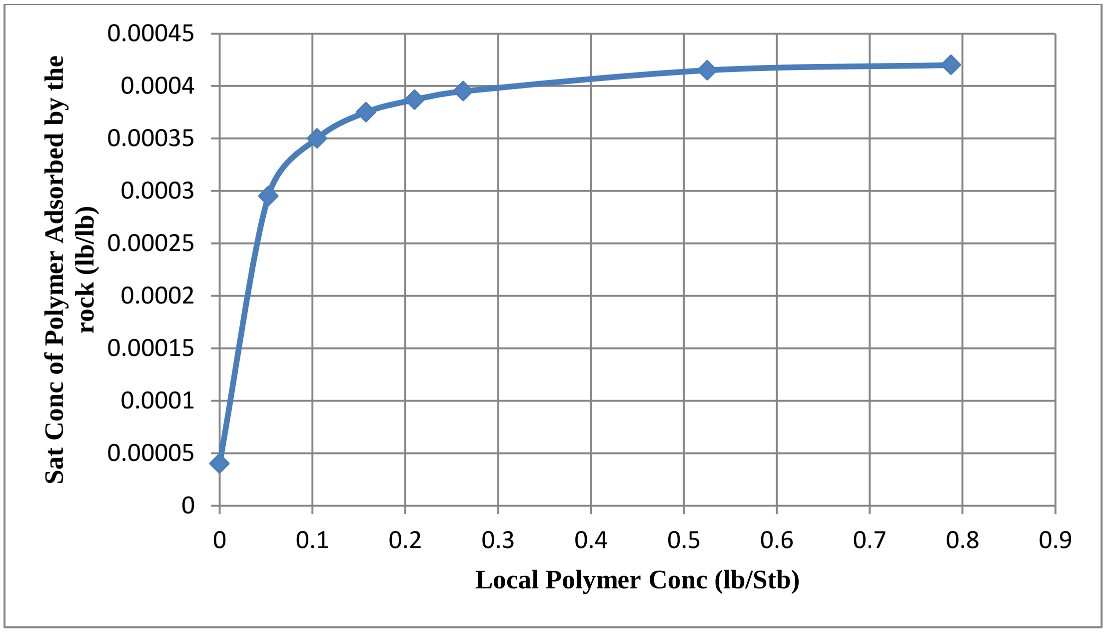


Figure 5.9: Local Polymer Concentration v/s Sat. Polymer Conc. Adsorbed by the rock

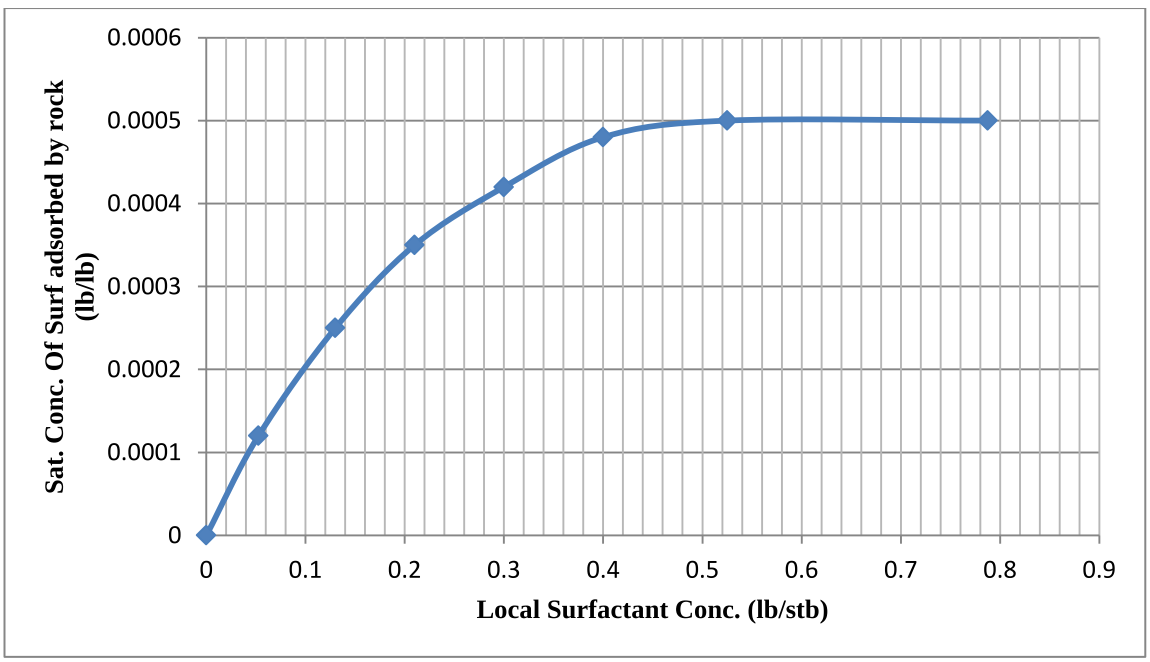


Figure 5.10: Local Surfactant Conc. v/s Surfactant Conc. Adsorbed by the rock

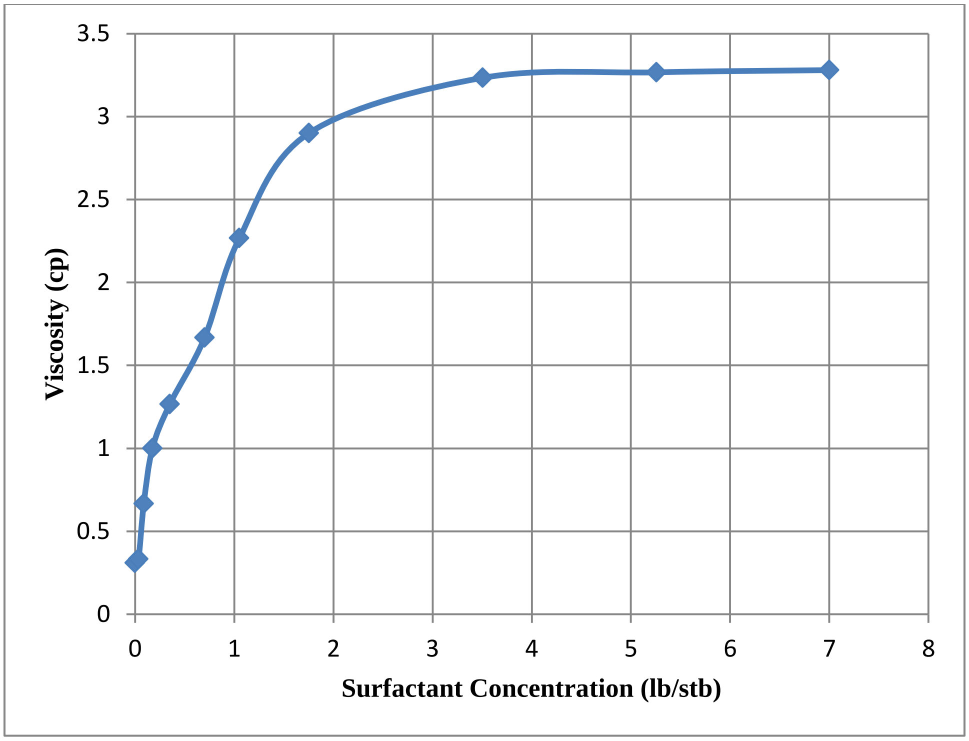


Figure 5.11: Surfactant Conc. v/s Water Viscosity at Reference Pressure

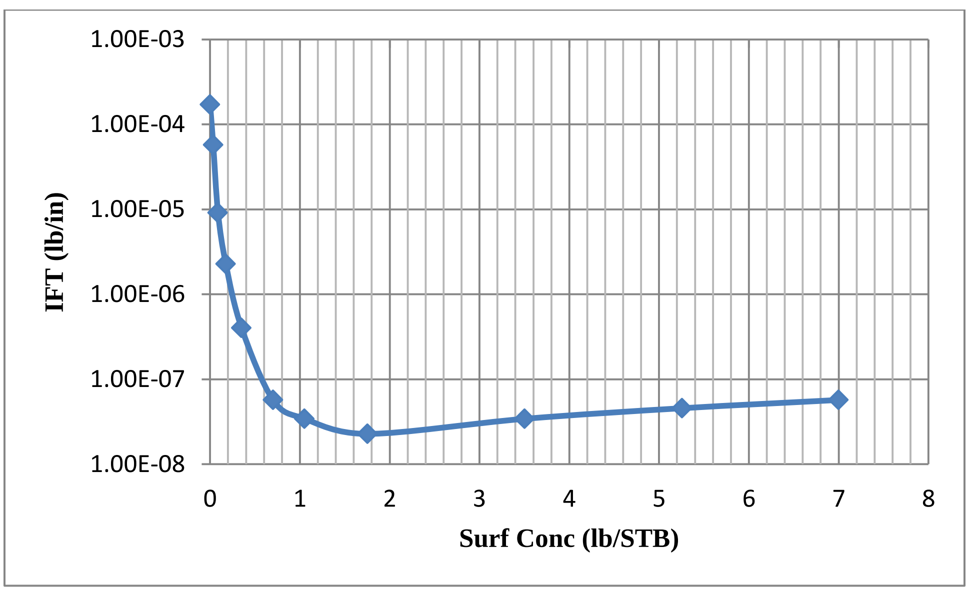


Figure 5.12: Surfactant Conc. v/s Water-Oil Interfacial Tension

5.5 Objective Functions

This research used two economic parameters to be maximized for the optimum values of optimized parameters. The economic parameters are:

1. Net Present Value (NPV)
2. Ultimate Recovery (UR)

The SP flood process consists of four flooding sequences

1. Water Flooding
2. Surfactant Flooding
3. Polymer Flooding
4. Post-Water Flooding

The simulation time duration for NPV calculations is 30 years (10950 days) and for Ultimate Recovery (UR) calculations is 200 years (73000 days). The results shown the time duration for water-flooding, surfactant flooding and polymer flooding. However, post-water flooding is calculated by taking the difference of total simulation time and the above mentioned flooding time.

The population size is determined from the formula:

$$Population\ Size = 4 + floor\{3 * \log(\mathrm{d})\}$$

where,

d is the number of optimized parameters

5.5.1 Net Present Value (NPV)

The concept of Net Present Value is based on the phrase ‘Money received sooner is worth more than money received later’. The NPV is dependent on the net cash flow discounted to the beginning of the project.

Net cash flow is given by the formula

$$\boldsymbol{Net\ Cash\ Flow = Net\ Annual\ Revenue\ - Net\ Annual\ Expenditure} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(5.1)}$$

Cost can be divided into two major categories namely

- Capital Expenditure (CAPEX)

The non-periodic cost incurred on purchasing major facilities either at the beginning of the project or during the life of the project is termed as ‘Capital Expenditure’ (CAPEX). It consists mainly of drilling cost and facility cost.

- Operating Expenditure (OPEX)

The periodic expenditure of a project is termed as ‘Operating Expenditure’ (OPEX)

Hence the economic analysis of this research includes oil price, operating cost including produced water handling and water/surfactant/polymer injection, discount rate and chemical price as the most important economic variables.

The Net Present Value can be calculated as

$$\boldsymbol{NPV = \sum_{i=1}^{N} \frac{\left(OPR.\$_{oil} - W_{prod}.\$_{water\ prod} - W_{inj}.\$_{water\ inj} - Chem.\$_{chemical}\right)_i.\Delta t_i}{(1+r)^{t_i}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(5.2)}$$

where,

OPR = Field oil production rate (STB/time step)

W_{prod} = Field waterproduction rate (STB/ time step)

W_{inj} = Field water injection rate (STB/ time step)

Chem = Field chemical (surfactant + polymer) injection rate (lbs/bbl)

$\$_{oil}$ = Cost of oil ($/STB)

$\$_{water\ prod}$ = Cost of handling produced water ($/STB)

$\$_{water\ inj}$ = Cost of water injection ($/STB)

$\$_{chemical}$ = Cost of chemical ($/lb)

i = time step counter

t_i = time value for i^{th} time step

Δt_i = time interval for i^{th} time step

r = discount rate (%)

The SP flooding with well placement optimization is done for Reservoir Model-1 and Model-2 using stochastic optimization algorithms having net present value (NPV) as an objective function to be maximized. The results of the optimization are discussed in the following subsections.

5.5.1.1 Case-1: NPV Optimization for Reservoir Model-1 (Channeled Reservoir)

Optimization study for Reservoir Model-1 is performed using three stochastic optimization algorithms namely Covariance Matrix Adaptation-Evolutionary Strategy (CMAES), Differential Evolution (DE) and Invasive Weed Optimization (IWO).

The optimization study is carried out using the following two subcases

1. Optimization of surfactant-polymer flooding with well placement optimization (See section 5.5.1.1.1)
2. Optimization of surfactant-polymer flooding without well placement optimization (See section 5.5.1.1.2)

In each of these subsections, three realizations of the three optimization algorithms (CMAES, DE and IWO) were generated and the Best, Median and Worst solutions were selected for analysis of performance. Furthermore, Section 5.5.1.1.3 compares the results of Sections 5.5.1.1.1 and 5.5.1.1.2.

5.5.1.1.1 Case-1a: SP Flooding with Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding with well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic evolutionary algorithms. Table 5.3 shows the input data for this case. Table 5.4 to Table 5.12, and Figs. 5.13 to 5.24 show the results obtained after optimization.

Table 5.3 shows that nine (9) producers and six (6) injectors were used for this case making a total of fifteen (15) wells. The number of (x,y) well locations to be determined is thirty (30) while the surfactant and polymer concentrations to be determined is two (2). Including time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 35.

Table 5.3: Case-1a: SP Flooding with Well Placement Optimization

Production Wells	9
Injection Wells	6
Reservoir Life (days)	10950
Number of Variables	35
Number of Generations	145
Population Size	14
Function Evaluation	2030
Number of Realizations	3

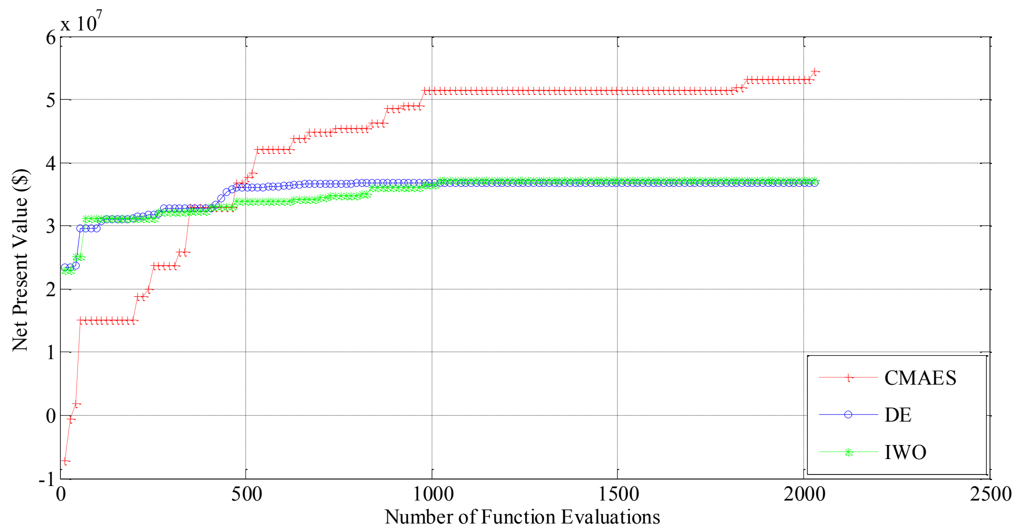


Figure 5.13: Comparison of Best Solution of CMAES, DE and IWO for Case-1a

Table 5.4: Best Solution of CMAES for Case-1a

<table>
<tr><th colspan="10">Optimized Variables</th><th rowspan="2">NPV</th></tr>
<tr><th>No.</th><th colspan="2">Production Wells</th><th colspan="2">Injection Wells</th><th>Duration for Water Flooding</th><th>Duration for Surfactant Flooding</th><th>Duration for Polymer Flooding</th><th>Surfactant Conc.</th><th>Polymer Conc.</th></tr>
<tr><th></th><th>x</th><th>y</th><th>x</th><th>y</th><th>days</th><th>days</th><th>days</th><th>lb/STB</th><th>lb/STB</th><th>$</th></tr>
<tr><td>1</td><td>30</td><td>30</td><td>30</td><td>30</td><td rowspan="9">7025</td><td rowspan="9">105</td><td rowspan="9">1825</td><td rowspan="9">0.2281</td><td rowspan="9">0.01</td><td rowspan="9">5.4480E+07</td></tr>
<tr><td>2</td><td>30</td><td>30</td><td>30</td><td>30</td></tr>
<tr><td>3</td><td>30</td><td>30</td><td>27</td><td>30</td></tr>
<tr><td>4</td><td>30</td><td>1</td><td>28</td><td>30</td></tr>
<tr><td>5</td><td>30</td><td>1</td><td>30</td><td>4</td></tr>
<tr><td>6</td><td>30</td><td>30</td><td>30</td><td>30</td></tr>
<tr><td>7</td><td>30</td><td>30</td><td></td><td></td></tr>
<tr><td>8</td><td>30</td><td>30</td><td></td><td></td></tr>
<tr><td>9</td><td>30</td><td>30</td><td></td><td></td></tr>
</table>

Table 5.5: Best Solution of DE for Case-1a

Optimized Variables											
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	1	1	1	2	7658	1095	147	0.1763	0.0014	**3.6797E+07**
2	30	30	1	1						
3	1	30	28	1						
4	2	30	7	1						
5	25	30	1	1						
6	30	4	14	1						
7	20	30								
8	9	30								
9	28	22								

Table 5.6: Best Solution of IWO for Case-1a

Optimized Variables										
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	4	26	13	1	4912	430	1258	0.48	1.00	**3.7242E+07**
2	10	30	19	1						
3	1	30	20	1						
4	27	27	16	2						
5	3	28	28	2						
6	26	30	28	1						
7	19	30								
8	16	29								
9	30	30								

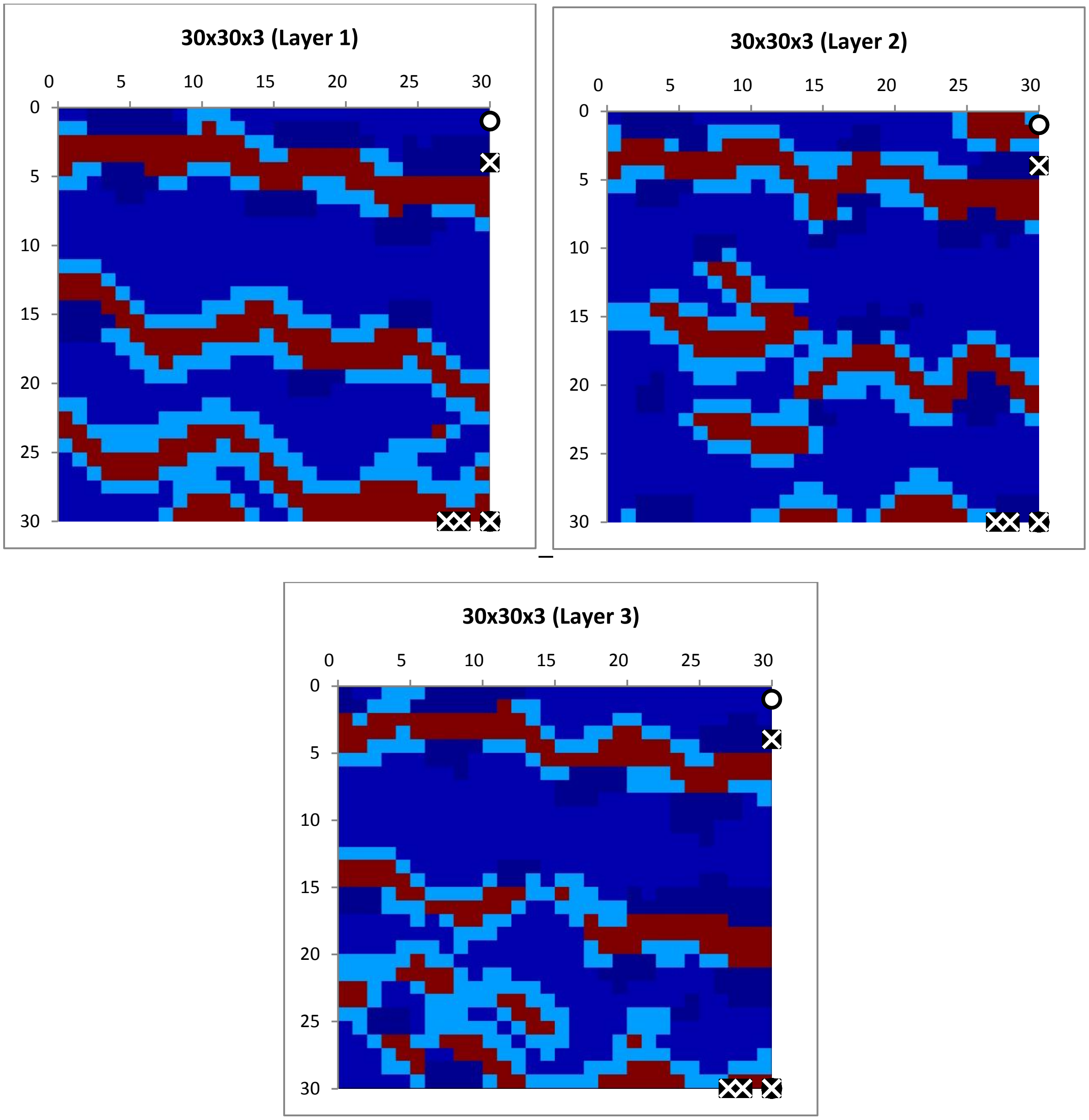


Figure 5.14: Best Solution of CMAES for Case-1a

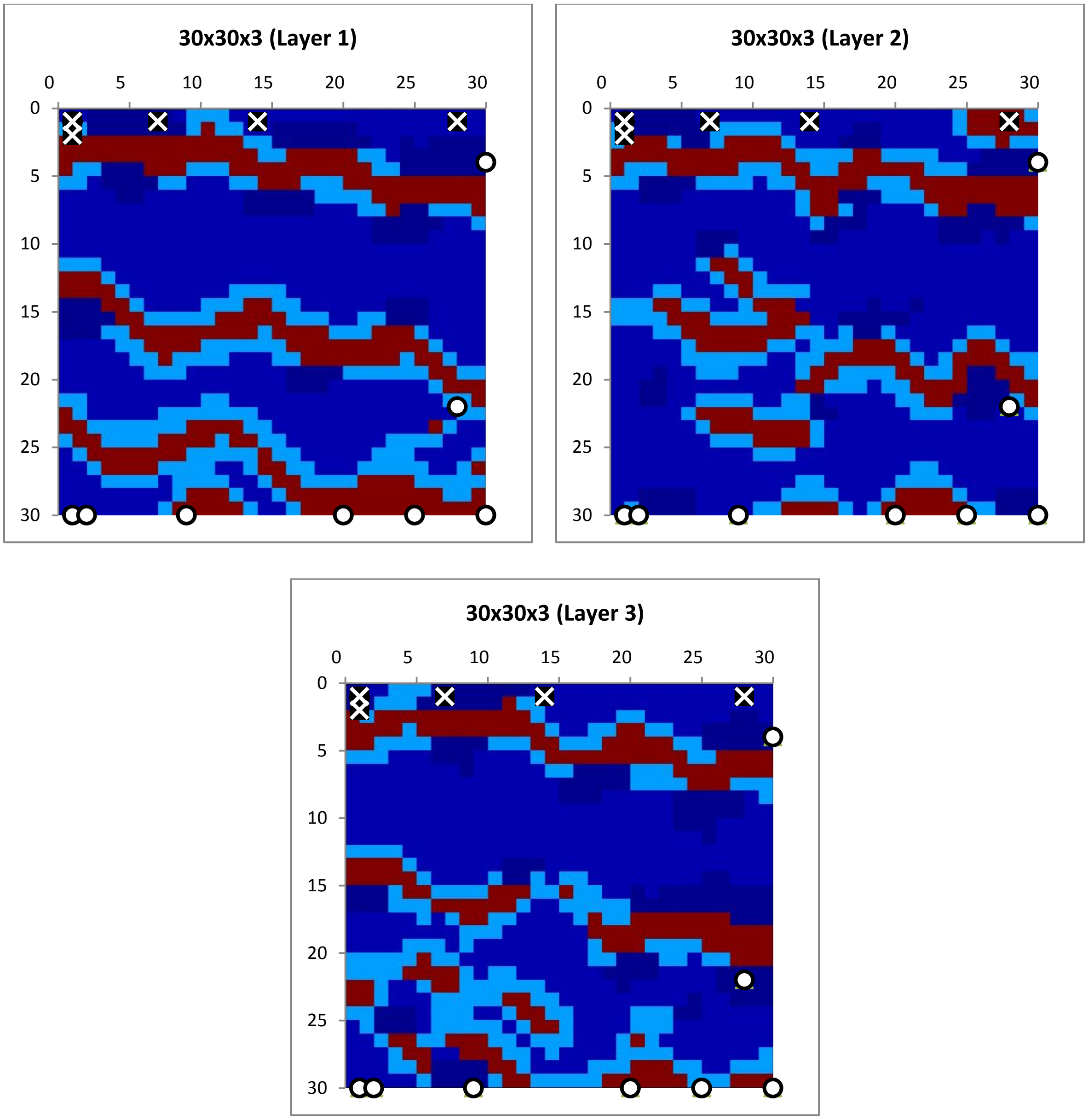


Figure 5.15: Best Solution of DE for Case-1a

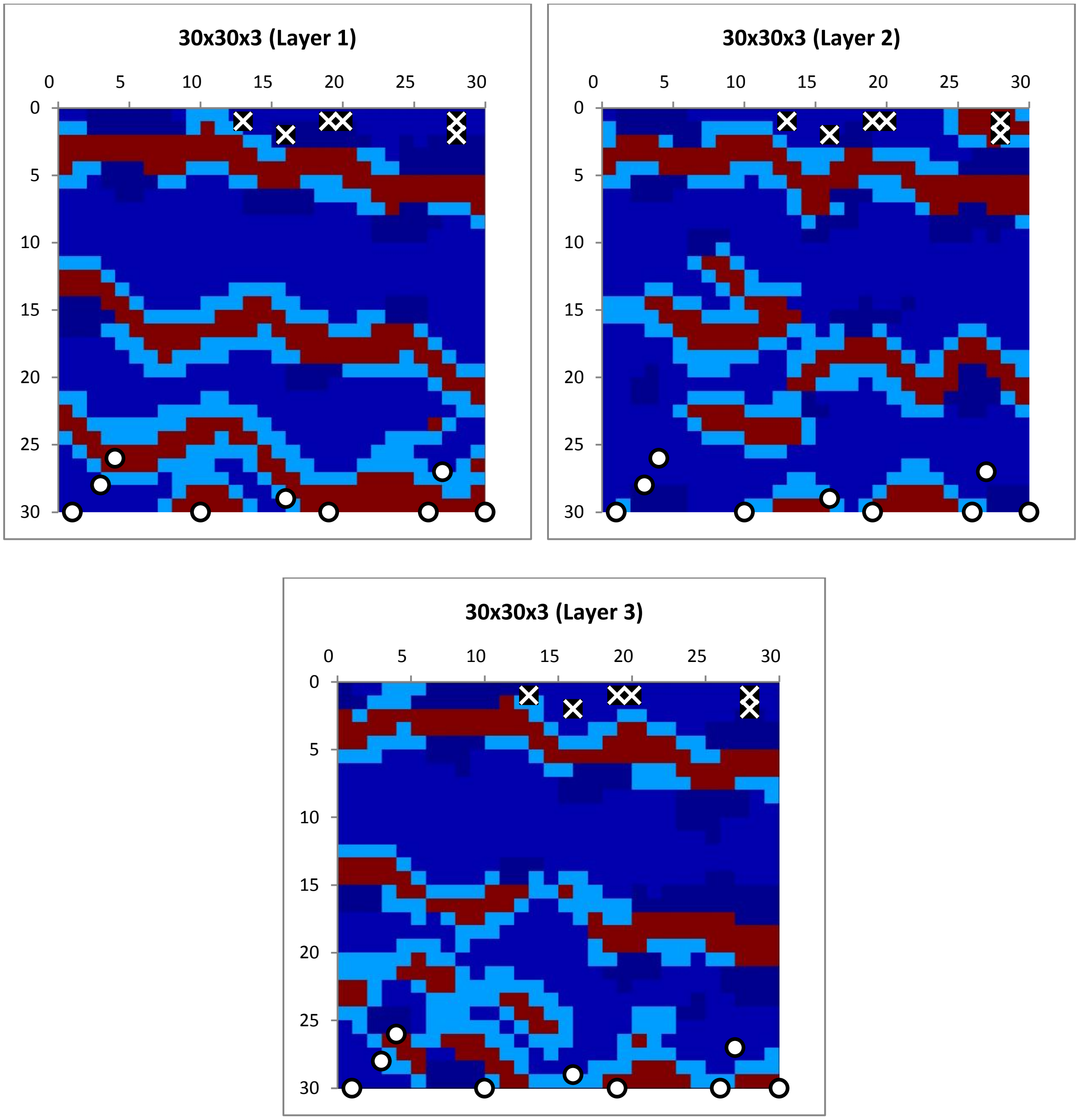


Figure 5.16: Best Solution of IWO for Case-1a

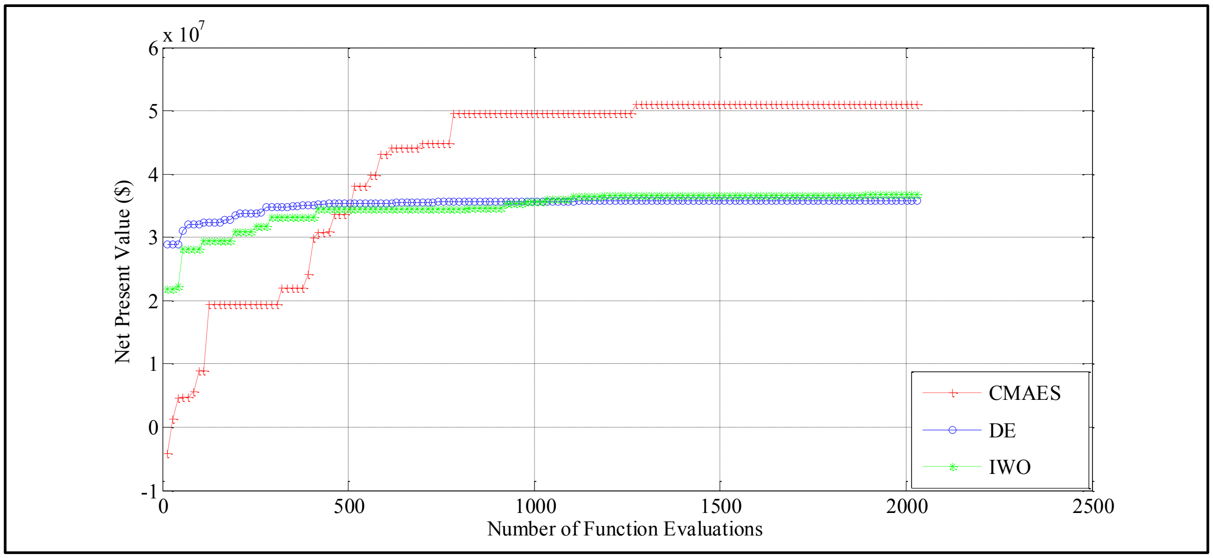


Figure 5.17: Comparison of Median Solution of CMAES, DE and IWO for Case-1a

Table 5.7: Median Solution of CMAES for Case-1a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	26	29	30	30						
2	30	30	30	30						
3	1	30	30	30						
4	1	30	1	30						
5	2	30	1	30	7665	0	0	0	0	**5.0977E+07**
6	30	30	29	30						
7	30	30								
8	1	29								
9	24	30								

Table 5.8: Median Solution of DE for Case-1a

Optimized Variables											NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.		
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**		**$**
1	30	2	17	25	5354	0	1825	0.00	0.96		**3.5768E+07**
2	1	1	30	27							
3	30	4	30	28							
4	16	1	30	17							
5	12	1	20	26							
6	11	1	28	26							
7	6	1									
8	1	30									
9	1	2									

Table 5.9: Median Solution of IWO for Case-1a

Optimized Variables											NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.		
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**		**$**
1	27	29	30	3	5791	317	1627	0.05	1.00		**3.6849E+07**
2	9	30	22	1							
3	19	29	6	5							
4	2	27	17	1							
5	6	27	29	3							
6	29	29	30	1							
7	4	30									
8	8	30									
9	28	23									

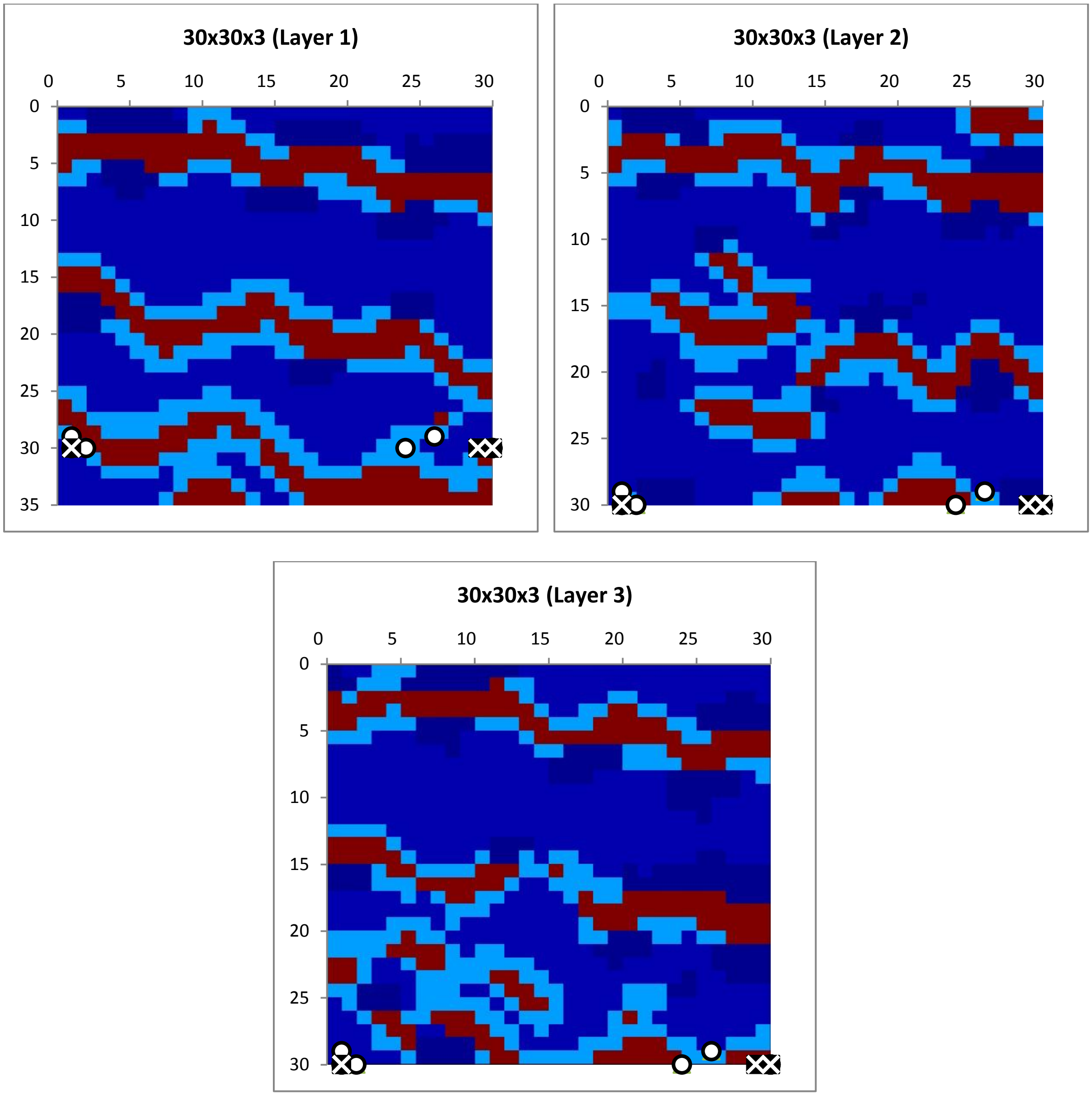


Figure 5.18: Median Solution of CMAES for Case-1a

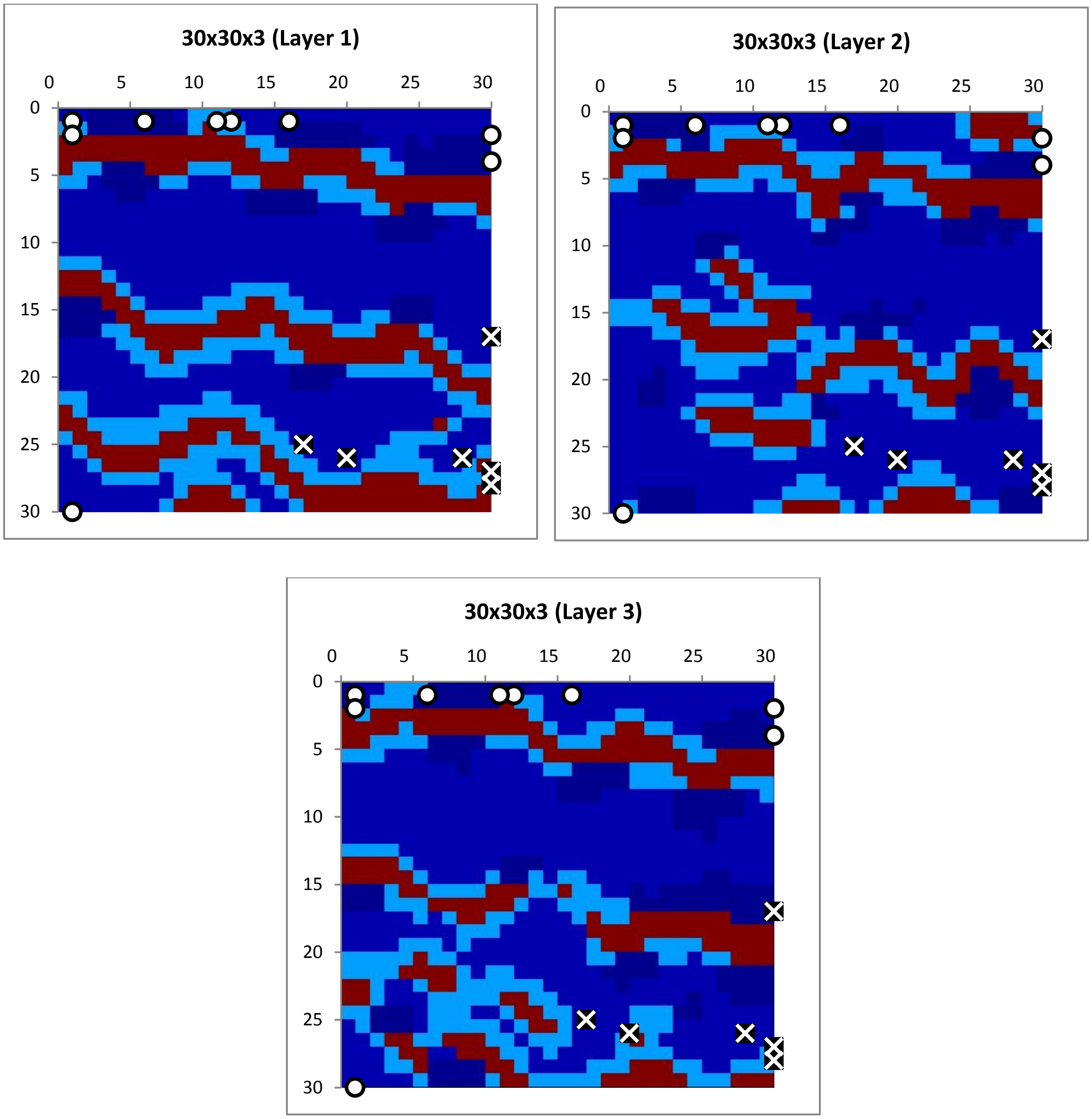


Figure 5.19: Median Solution of DE for Case-1a

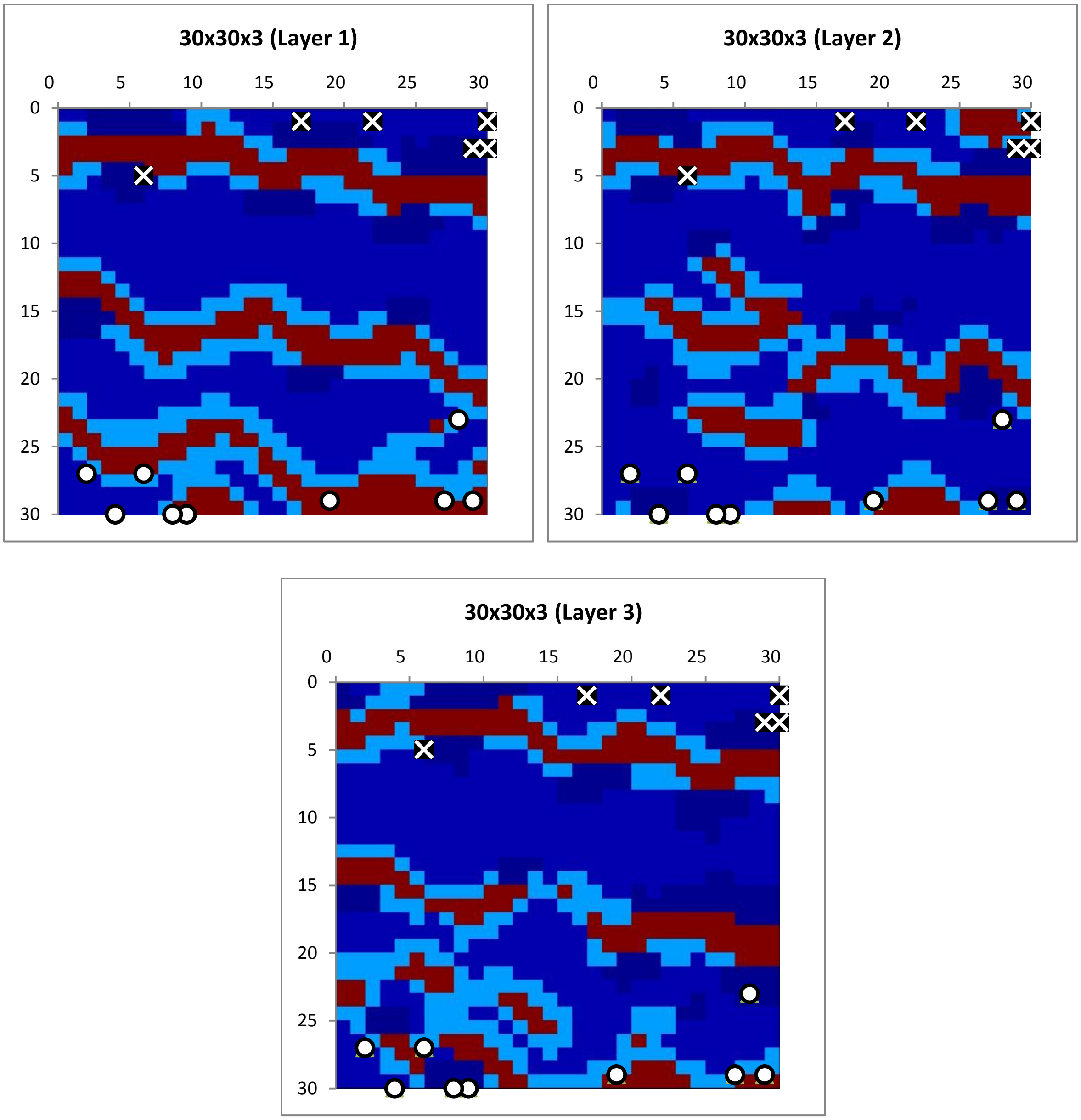


Figure 5.20: Median Solution of IWO for Case-1a

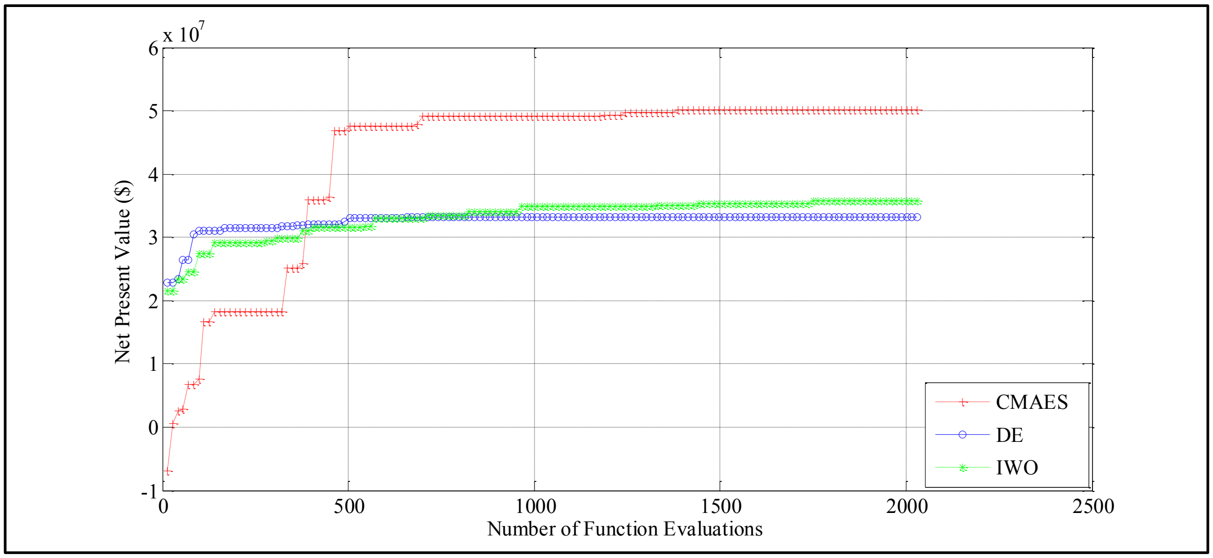


Figure 5.21: Comparison of Worst Solution of CMAES, DE and IWO for Case-1a

Table 5.10: Worst Solution of CMAES for Case-1a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	30	30	30	30	2285	0	0	0.00	0.00	**5.0196E+07**
2	30	30	30	30						
3	1	30	30	30						
4	6	2	1	29						
5	30	30	30	30						
6	30	30	30	30						
7	30	30								
8	1	29								
9	30	30								

Table 5.11: Worst Solution of DE for Case-1a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	7	2	1	30	5558	0	0	0.00	0.00	**3.3223E+07**
2	28	30	2	1						
3	30	29	1	1						
4	1	1	1	1						
5	26	28	1	2						
6	30	26	30	3						
7	1	20								
8	30	30								
9	2	1								

Table 5.12: Worst Solution of IWO for Case-1a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	2	26	29	6	7665	908	1296	0.92	0.75	**3.5793E+07**
2	2	25	27	1						
3	28	29	30	1						
4	17	24	15	3						
5	6	2	21	1						
6	1	30	22	6						
7	27	29								
8	23	28								
9	8	30								

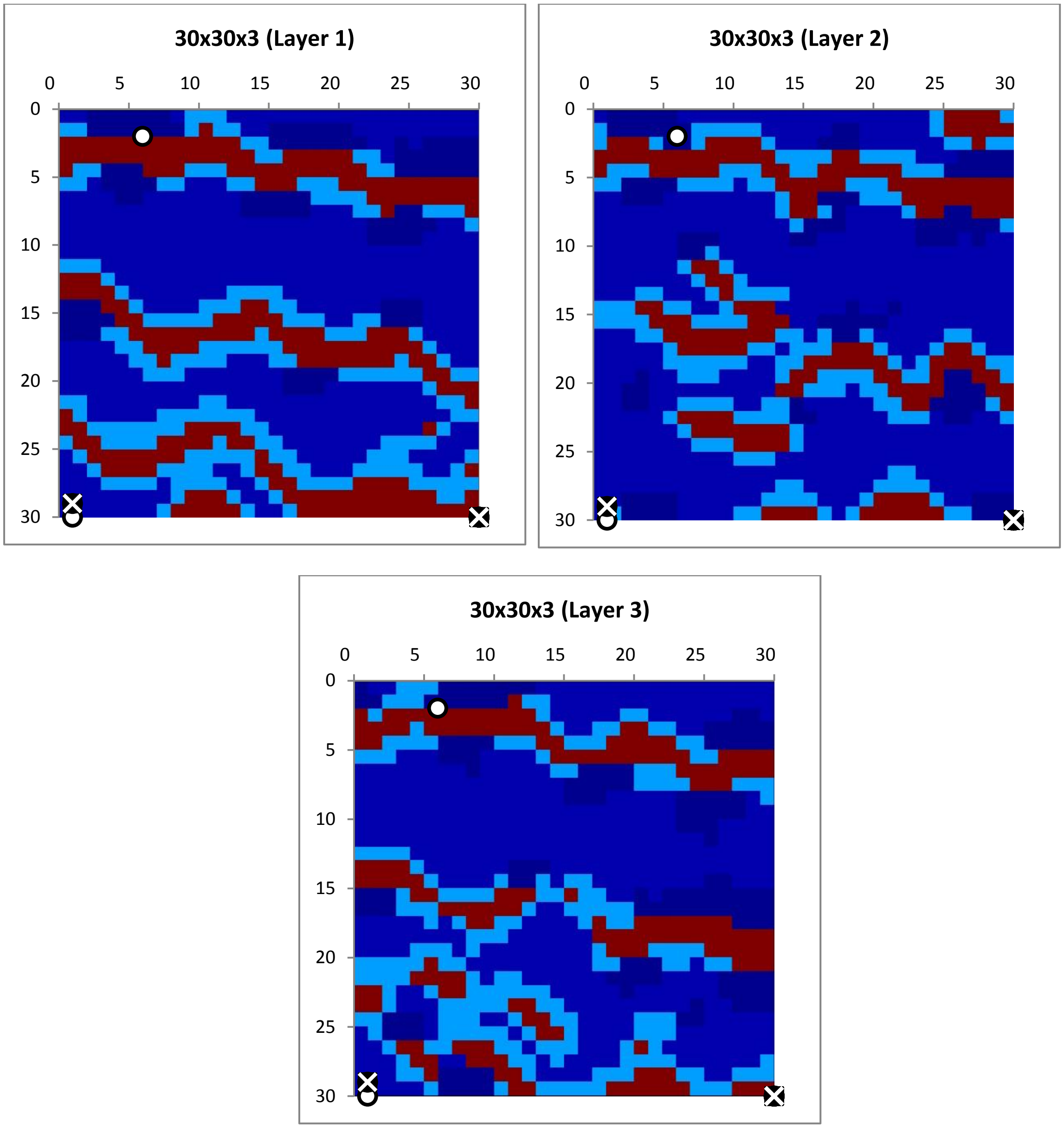


Figure 5.22: Worst Solution of CMAES for Case-1a

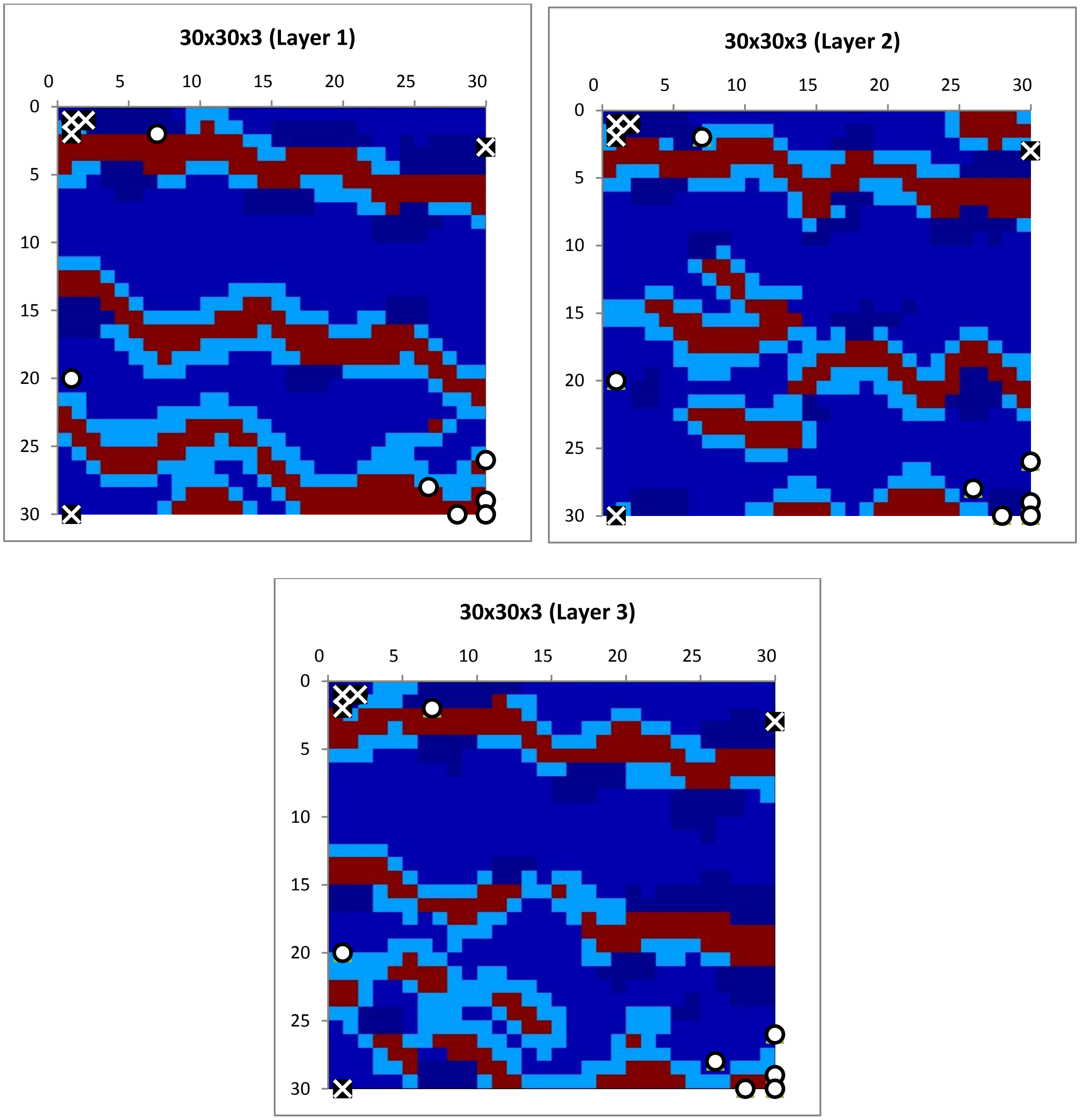


Figure 5.23: Worst Solution of DE for Case-1a

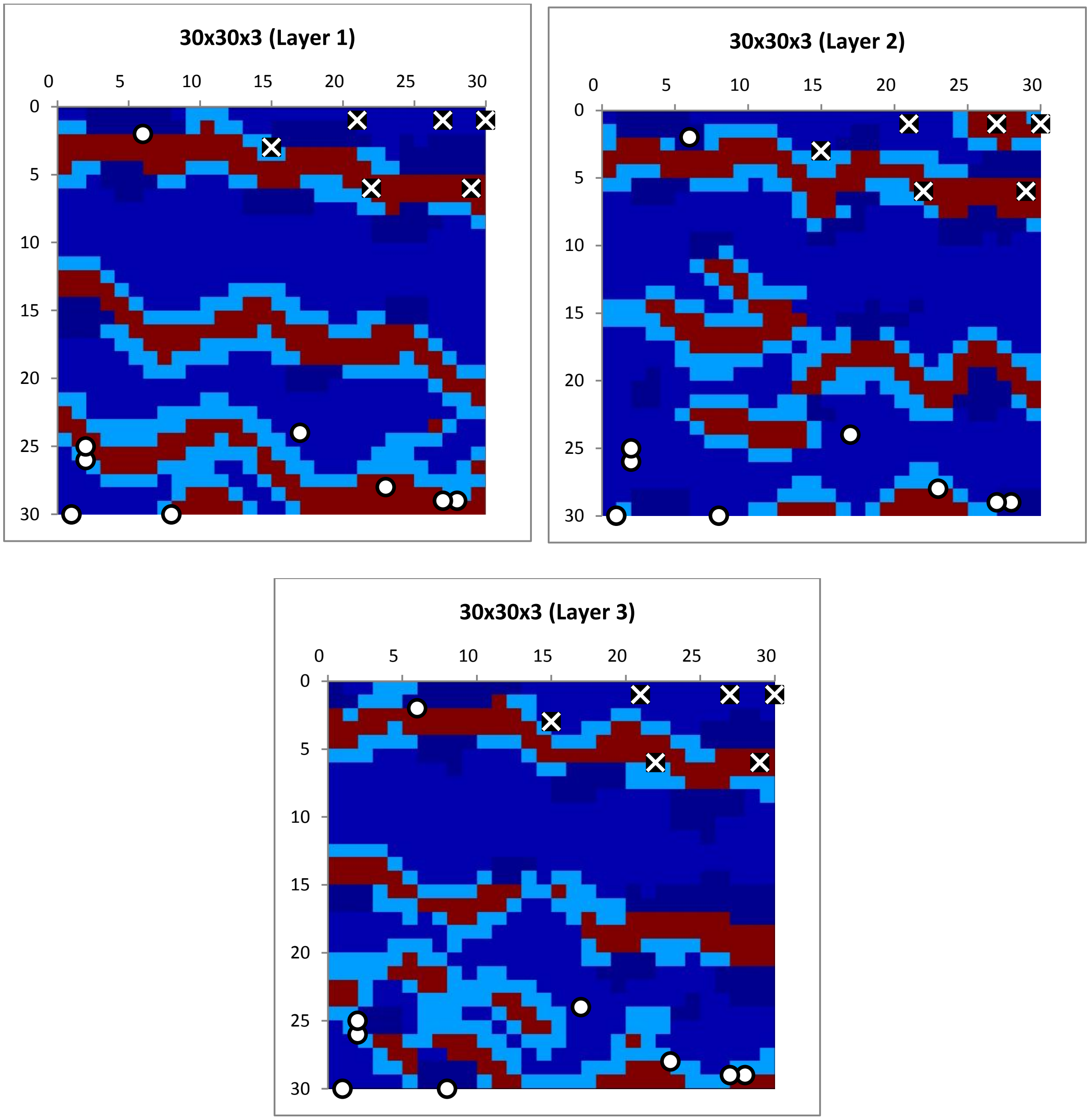


Figure 5.24: Worst Solution of IWO for Case-1a

Discussion

This is a summary of the results presented

NPV

CMAES showed highest values of NPV amongst the three stochastic algorithms for best, median and worst realizations. The results from DE and IWO are comparable however IWO showed marginally better results than DE in all realizations.

Convergence Pattern

CMAES showed continuously improving trend than DE and IWO for the same number of function evaluations. DE and IWO initially showed slight improvement but converges at a lower values of NPV than CMAES.

Consistency

The three techniques remained almost consistent for this case.

EOR process Selection

The three techniques showed variable EOR process selection for best, median and worst realizations. CMAES showed higher values of NPV than DE and IWO but poor well placement configuration. However, considering the NPV values, convergence, consistency and well placement configuration, IWO is considered as the most suitable technique for this case. The selected EOR process configuration for this case is waterflooding followed by surfactant flooding and then polymer flooding.

Well Placement

DE and IWO invariably showed placement of producers and injectors around the periphery of the reservoir in the channels having high and low permeability values respectively. CMAES showed poor well placement configuration. However in DE and IWO, the overlapping of wells in some realizations can be resolved by combining the total liquid rate constraint of more than one well in single well if the wells are of the same type (producer). If there is an overlapping of different well types (injector & producer), then the configuration is invalid. In case of clustering of wells in one location, check the minimum well spacing that guarantees the safety of each well. If it is met than that configuration is valid, otherwise not.

It is also evident from the well placement configuration that high NPV values can be achieved by placing producers and injectors in high and low permeability zones respectively using peripheral injection scheme.

5.5.1.1.2 Case-1b: SP Flooding without Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding without well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic optimization algorithms. Table 5.13 shows the input data for this case. Table 5.14 to Table 5.22, and Figs. 5.26 to 5.28 show the results obtained after optimization. Table 5.13 shows that nine (9) producers and six (6) injectors were used for this case and their locations are fixed as shown in Fig. 5.25. The surfactant and polymer concentrations in injection wells to be determined is two (2). Including the time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 5.

Table 5.13: Case-1b: SP Flooding without Well Placement Optimization

Production Wells	9
Injection Wells	6
Reservoir Life (days)	10950
Number of Variables	5
Number of Generations	75
Population Size	8
Function Evaluation	600
Number of Realizations	3

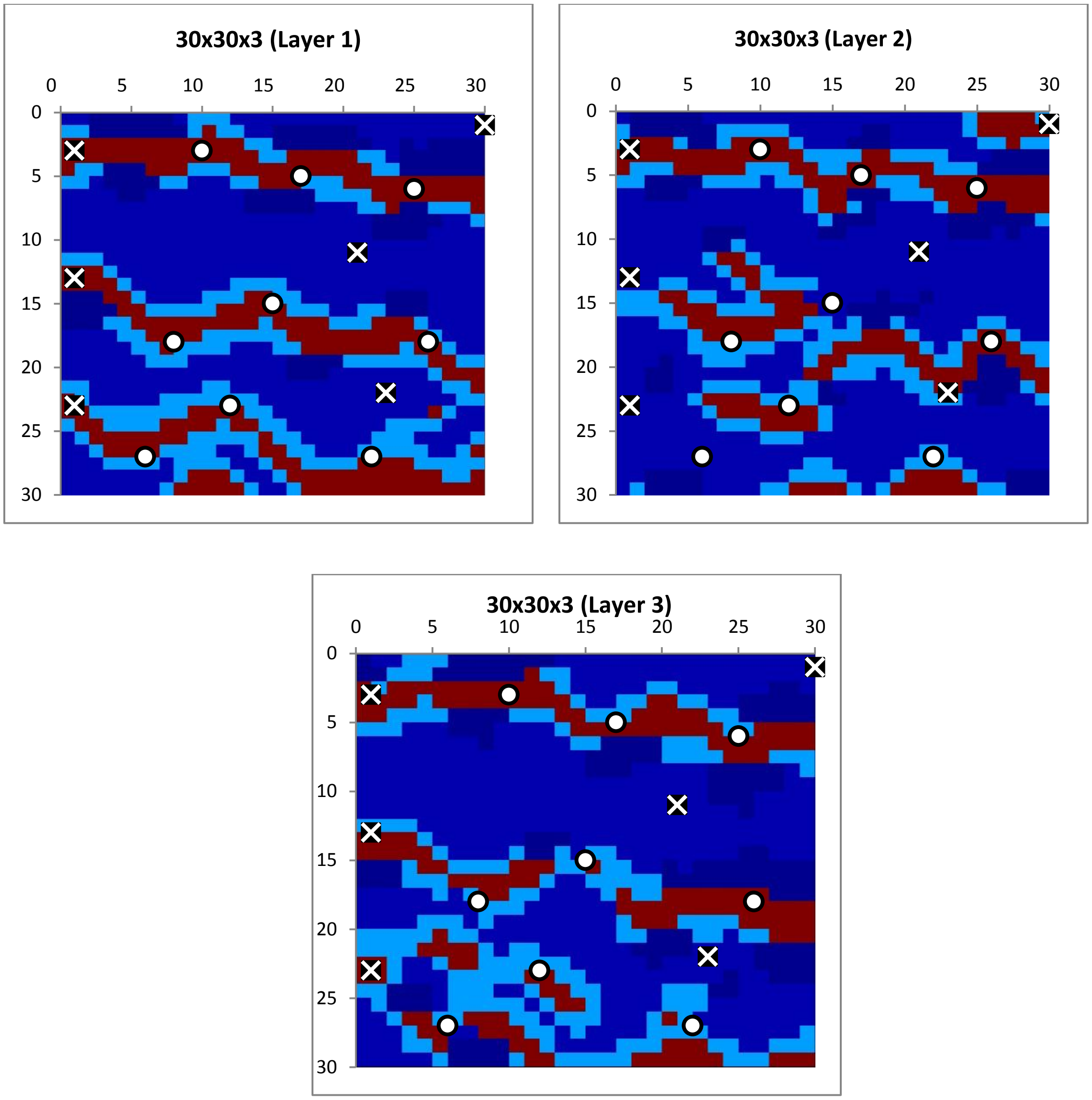


Figure 5.25: Well Locations for Case-1b

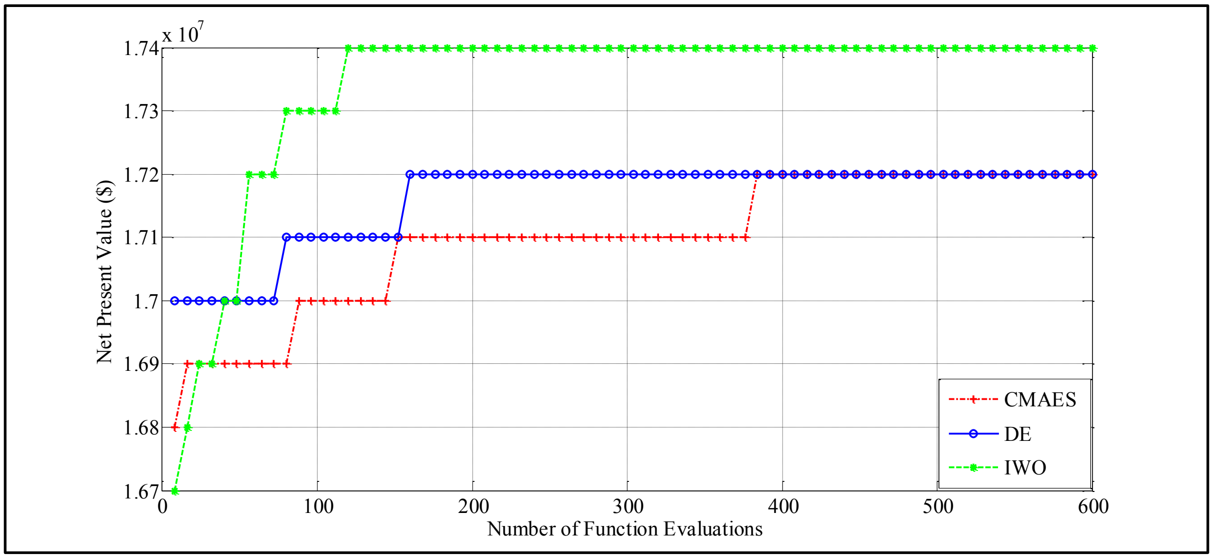


Figure 5.26: Comparison of Best Solution of CMAES, DE and IWO for Case-1b

Table 5.14: Best Solution of CMAES for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables					**NPV**
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	5959	47	152	0.45	0.97	**1.7203E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.15: Best Solution of DE for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	6011	5	170	0.02	0.99	**1.7204E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.16: Best Solution of IWO for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	4920	0	1825	0.00	1.00	**1.7383E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

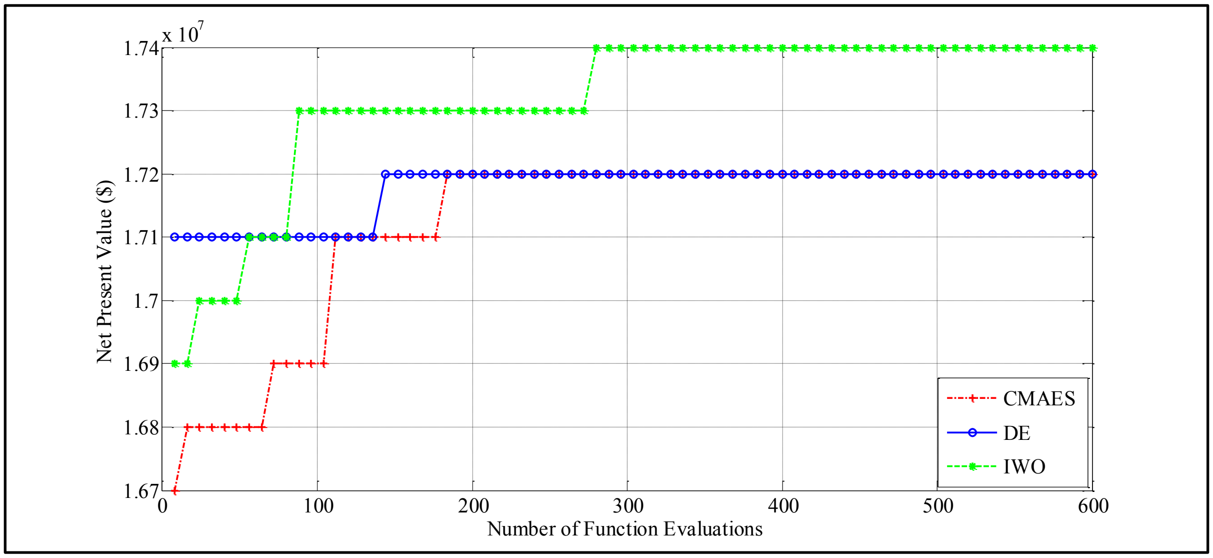


Figure 5.27: Comparison of Median Solution of CMAES, DE and IWO for Case-1b

Table 5.17: Median Solution of CMAES for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables					NPV
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	y	x	y	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	5898	101	137	0.46	0.97	**1.7202E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.18: Median Solution of DE for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	5950	92	187	1.00	1.00	**1.7188E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.19: Median Solution of IWO for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	4947	0	1825	0.00	1.00	**1.7381E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

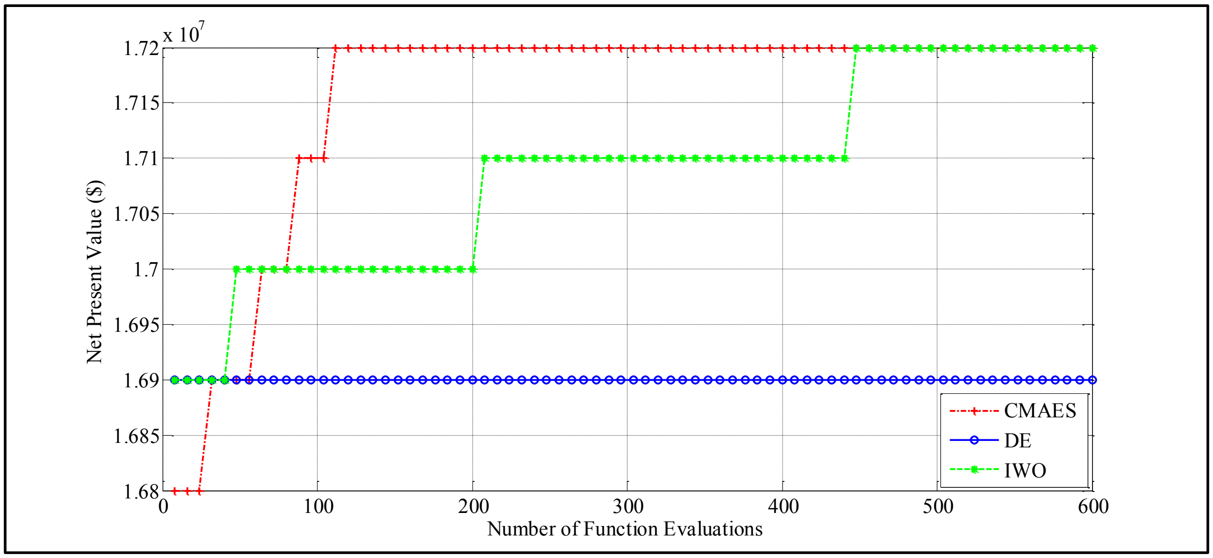


Figure 5.28: Comparison of Worst Solution of CMAES, DE and IWO for Case-1b

Table 5.20: Worst Solution of CMAES for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables					NPV
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	5928	130	142	0.67	1.00	**1.7177E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.21: Worst Solution of DE for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	6430	801	249	2.27E-04	0.42	**1.6918E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Table 5.22: Worst Solution of IWO for Case-1b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	15	15	21	11	5820	230	151	0.13	1.00	**1.7175E+07**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	23	22						
7	25	6								
8	12	23								
9	26	18								

Discussion

This is the summary of the results presented

NPV

IWO showed highest values of NPV amongst the three stochastic algorithms for best and median realizations while its result in the worst realization case is comparable with that of CMAES. The results from CMAES and DE are comparable for best and median realizations while DE showed lowest NPV value for worst realization.

Convergence Pattern

It is evident from the results that IWO showed considerable improvement in the convergence towards the higher optimized solution. CMAES and DE showed early convergence in all realizations.

Consistency

The three techniques remained almost consistent for this case except DE for the worst realization where it slightly improved and converged.

EOR process Selection

The three techniques showed almost the same EOR process selection for best, median and worst realizations. However the selected EOR process configuration for the highest value of NPV for this case is from IWO which is waterflooding followed by polymer flooding without surfactant flooding.

5.5.1.1.3 Comparison of Case-1a, Case-1b and Waterflooding

A base case having fixed well locations with simple waterflooding was run and compared with SP flooding process with well placement optimization (Case-1a) and SP flooding process without well placement optimization (Case-1b). Well placement configuration for the base case and Case-1b remains the same. Table 5.23, Figs. 5.29 and 5.30 showed the summary of Case-1a, Case-1b and waterflooding for best, median and worst realizations for Reservoir Model-1. The incremental NPV values are calculated by comparing each of Case-1a and Case-1b with waterflooding.

It is evident from the results that there is an increase in the NPV after the implementation of stochastic optimization techniques. The increase in NPV is in the range of 0.60% to 3.37% when SP flooding is optimized without well placement optimization (Case-1b). However, SP flooding with well placement optimization (Case-1a) showed increase in NPV in the range of about 97.56% to 223.96%.

Table 5.23: Comparison of Case-1a, Case-1b and Waterflooding

Stochastic Technique	Solution Type	SP Flooding with WPO (Case-1a)	SP Flooding without WPO (Case-1b)	Water flooding	Incremental NPV (Case-1a)	Incremental NPV (Case-1b)
		million $	million $	million $	%	%
CMAES	Best	54.48	17.20	16.82	223.96	2.30
	Median	50.98	17.20	16.82	203.13	2.29
	Worst	50.20	17.18	16.82	198.49	2.14
DE	Best	36.80	17.20	16.82	118.81	2.30
	Median	35.77	17.19	16.82	112.69	2.21
	Worst	33.22	16.92	16.82	97.56	0.60
IWO	Best	37.24	17.38	16.82	121.46	3.37
	Median	36.85	17.38	16.82	119.12	3.36
	Worst	35.79	17.18	16.82	112.84	2.13

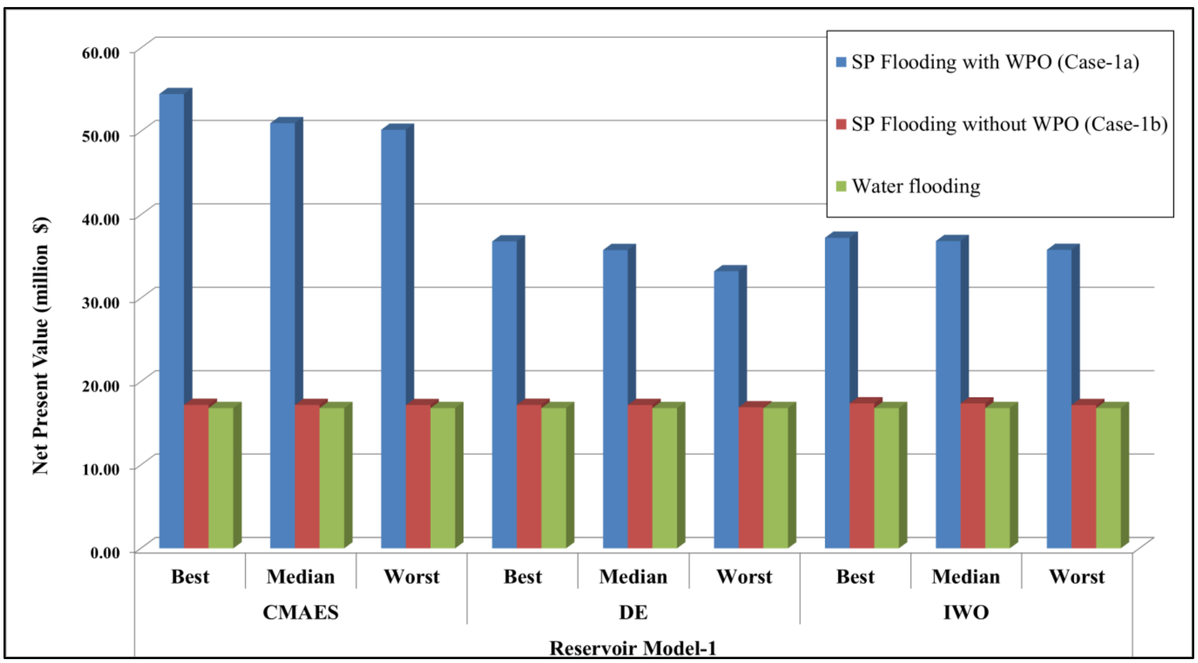


Figure 5.29: Comparison of Case1a, Case-1b and Waterflooding

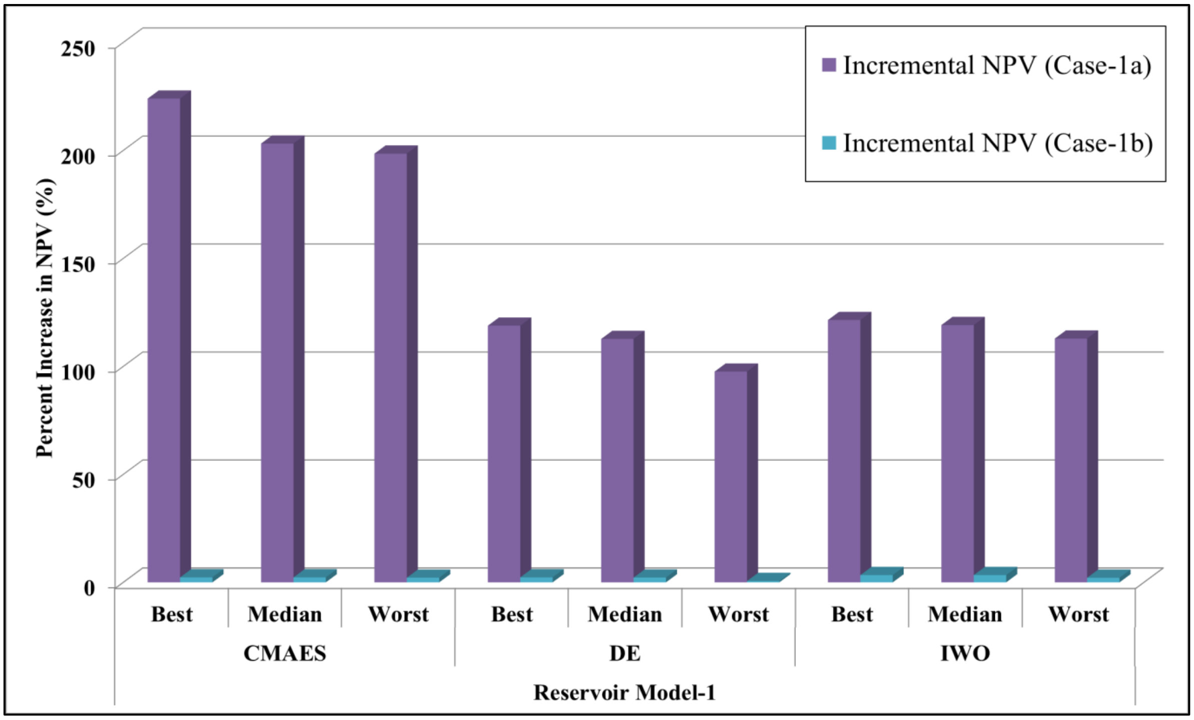


Figure 5.30: Incremental NPV from Case-1a and Case-1b

5.5.1.2 Case-2: NPV Optimization for Reservoir Model-2 (Heterogeneous Reservoir with Fully Distributed Permeability Field)

Optimization study for Reservoir Model-2 is performed using three stochastic optimization algorithms namely Covariance Matrix Adaptation-Evolutionary strategy (CMAES), Differential Evolution (DE) and Invasive Weed Optimization (IWO).

The optimization study is carried out using the following two subcases

1. Optimization of surfactant-polymer flooding with well placement (See section 5.5.1.2.1)
2. Optimization of surfactant-polymer flooding without well placement optimization (See section 5.5.1.2.2)

In each of these subsections, three realizations of the three optimization algorithms (CMAES, DE and IWO) were generated and the Best, Median and Worst solutions were selected for analysis of performance. Furthermore, Section 5.5.1.2.3 compares the results of Sections 5.5.1.2.1 and 5.5.1.2.2.

5.5.1.2.1 Case-2a: SP Flooding with Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding with well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic evolutionary algorithms. Table 5.24 shows the input data for this case. Table 5.25 to Table 5.33, and Figs. 5.31 to 5.42 show the results obtained after optimization.

Table 5.24 shows that thirteen (13) producers and twelve (12) injectors were used for this case making a total of twenty-five (25) wells. The number of (x,y) well locations to be determined is fifty (50) while the surfactant and polymer concentrations in injection wells to be determined is two (2). Including time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 55.

Table 5.24: Case-2a: SP Flooding with Well Placement Optimization

Production Wells	13
Injection Wells	12
Reservoir Life (days)	10950
Number of Variables	55
Number of Generations	190
Population Size	16
Function Evaluation	3040
Number of Realizations	3

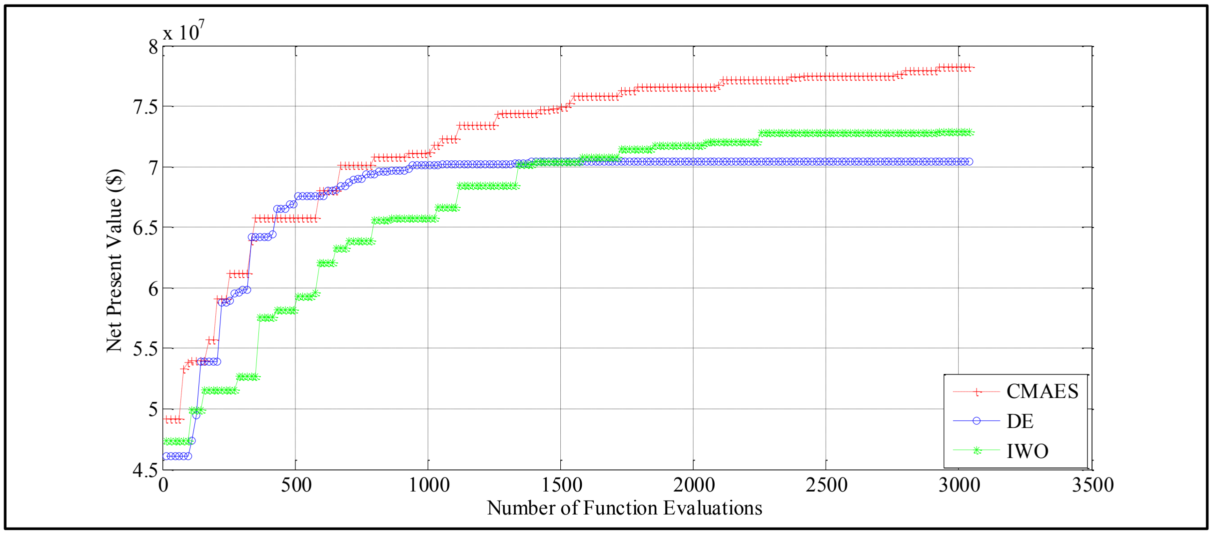


Figure 5.31: Comparison of Best Solution of CMAES, DE and IWO for Case-2a

Table 5.25: Best Solution of CMAES for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	48	2	42	43	4251	1095	1085	0.001	0.7554	**7.8203E+07**
2	13	45	45	48						
3	20	30	46	50						
4	40	19	41	38						
5	43	1	9	1						
6	18	33	1	1						
7	48	8	11	6						
8	34	22	15	2						
9	46	1	45	47						
10	2	44	13	1						
11	7	49	18	15						
12	11	36	15	13						
13	8	50								

Table 5.26: Best Solution of DE for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	6	47	36	50	4675	642	1051	0.001	0.30114	**7.03895E+07**
2	50	25	38	34						
3	49	24	24	41						
4	20	32	28	20						
5	1	32	32	46						
6	15	28	9	13						
7	36	15	31	24						
8	17	28	21	3						
9	15	45	20	11						
10	2	42	23	1						
11	6	10	21	8						
12	50	8	15	1						
13	49	40								

Table 5.27: Best Solution of IWO for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	1	33	48	3	4224	472	1702	0.0111	1	**7.29461E+07**
2	21	35	46	16						
3	8	31	50	2						
4	1	6	45	13						
5	2	42	50	49						
6	1	15	48	9						
7	1	2	45	5						
8	12	47	49	16						
9	6	33	50	12						
10	10	36	31	15						
11	16	42	50	19						
12	1	38	50	32						
13	2	46								

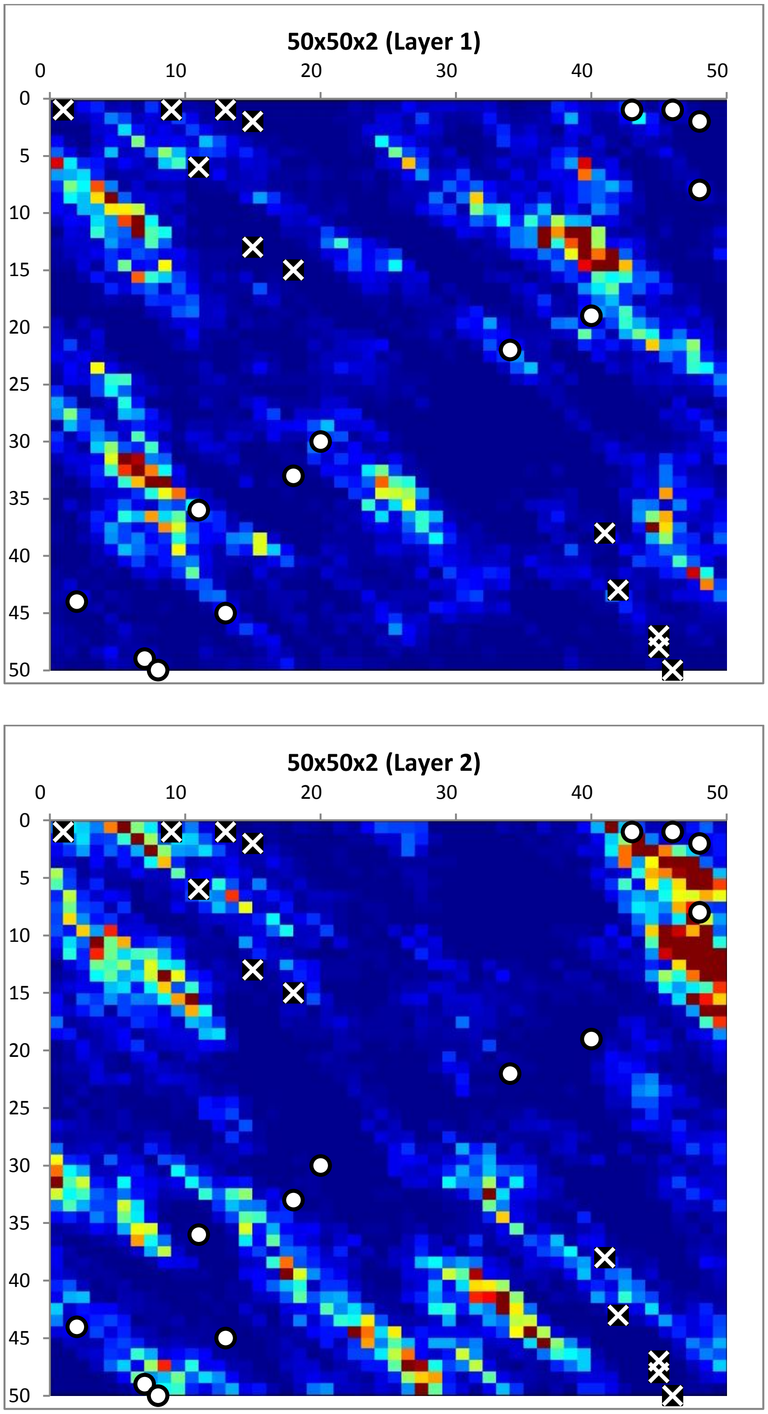


Figure 5.32: Best Solution of CMAES for Case-2a

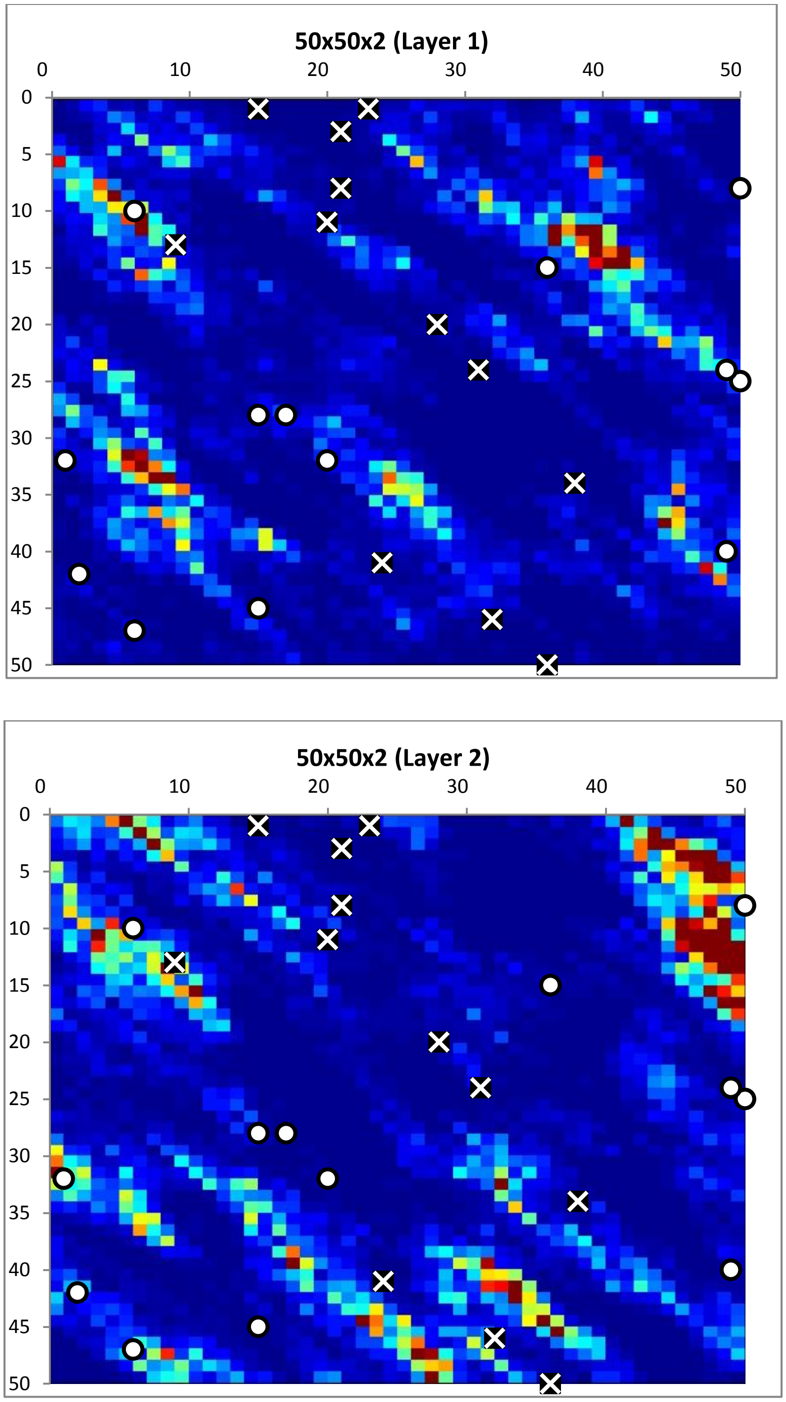
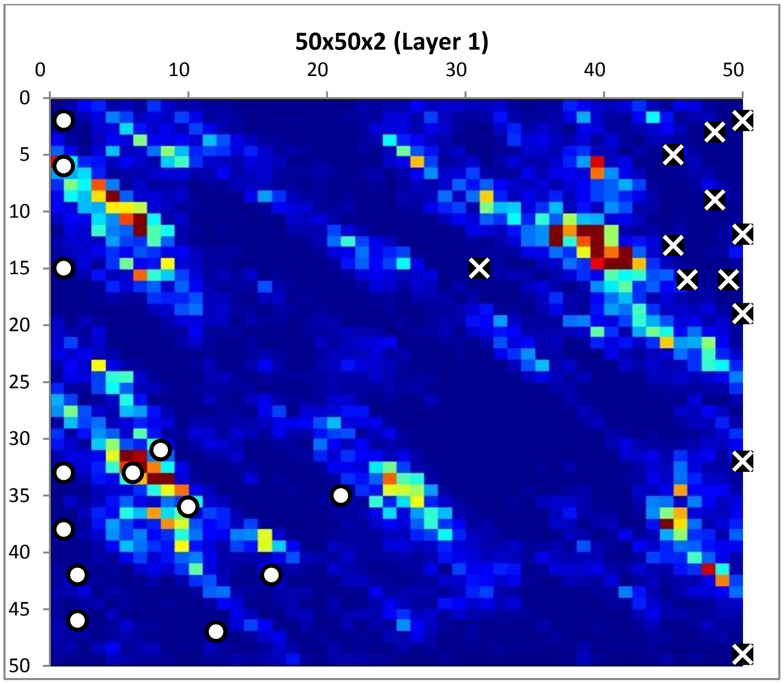


Figure 5.33: Best Solution of DE for Case-2a



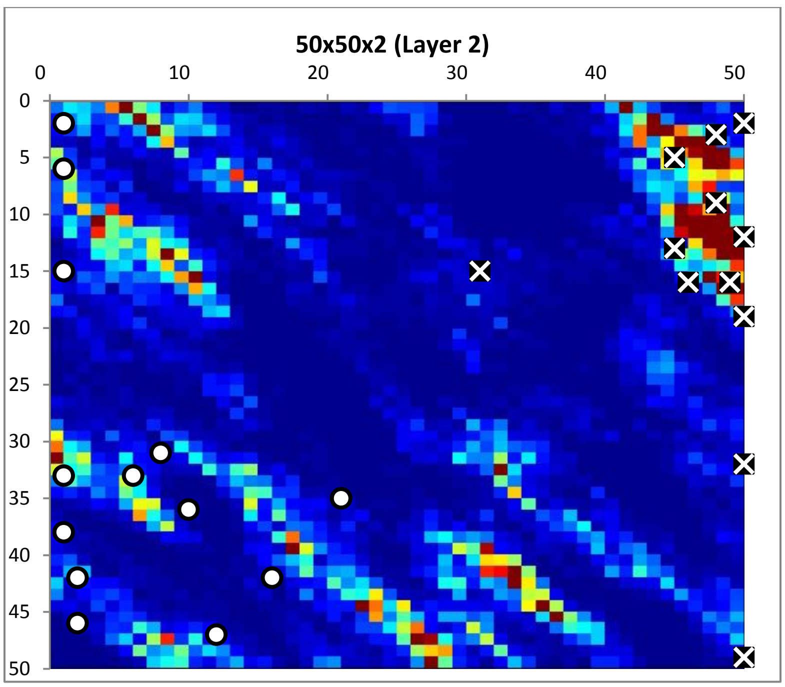


Figure 5.34: Best Solution of IWO for Case-2a

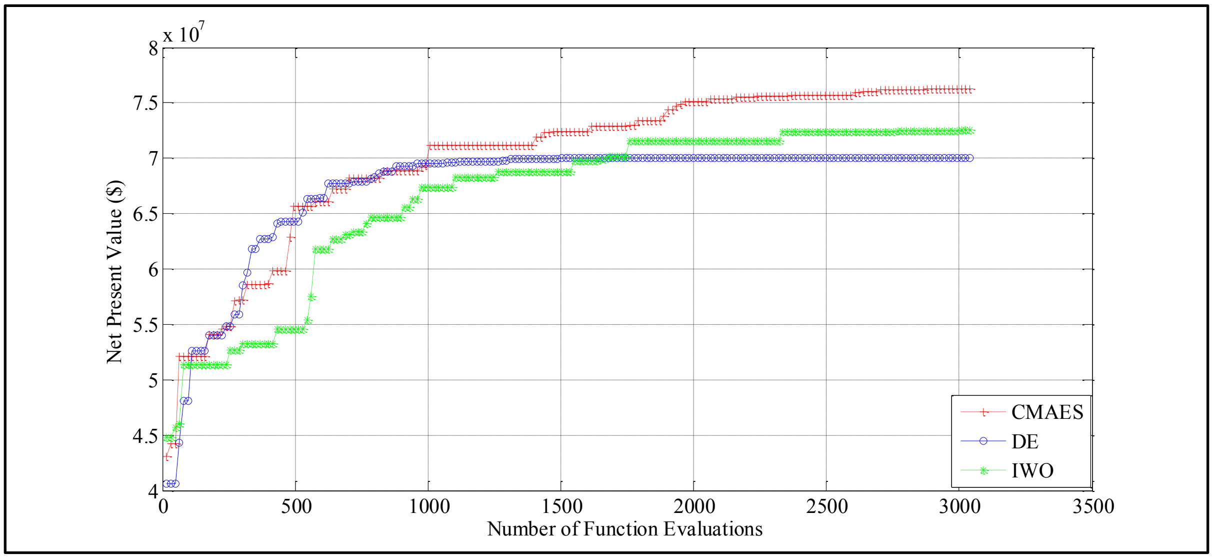


Figure 5.35: Comparison of Median Solution of CMAES, DE and IWO for Case-2a

Table 5.28: Median Solution of CMAES for Case-2a

Optimized Variables										**NPV**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	7	15	50	31						
2	4	19	50	28						
3	1	43	50	38						
4	1	26	49	28						
5	13	25	50	1						
6	3	7	45	1						
7	9	1	50	36	4221	26	1600	0.6155	0.9625	**7.6285E+07**
8	5	10	48	50						
9	7	11	50	29						
10	3	12	50	30						
11	1	44	50	49						
12	8	17	50	26						
13	20	24								

Table 5.29: Median Solution of DE for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	50	36	1	1	6144	765	1730	0.8415	0.1053	**6.9987E+07**
2	41	40	25	5						
3	22	46	24	13						
4	1	33	44	50						
5	26	48	1	3						
6	23	35	15	2						
7	37	36	10	1						
8	44	37	1	2						
9	33	33	1	47						
10	32	33	13	1						
11	50	6	24	12						
12	46	26	1	50						
13	31	42								

Table 5.30: Median Solution of IWO for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	10	1	50	42	4035	590	1570	0.5576	1	**7.2570E+07**
2	23	13	46	34						
3	20	9	43	39						
4	11	1	43	34						
5	8	10	50	2						
6	14	16	40	34						
7	1	46	50	38						
8	1	50	45	5						
9	16	6	49	47						
10	4	43	49	46						
11	3	19	38	30						
12	7	4	39	40						
13	6	4								

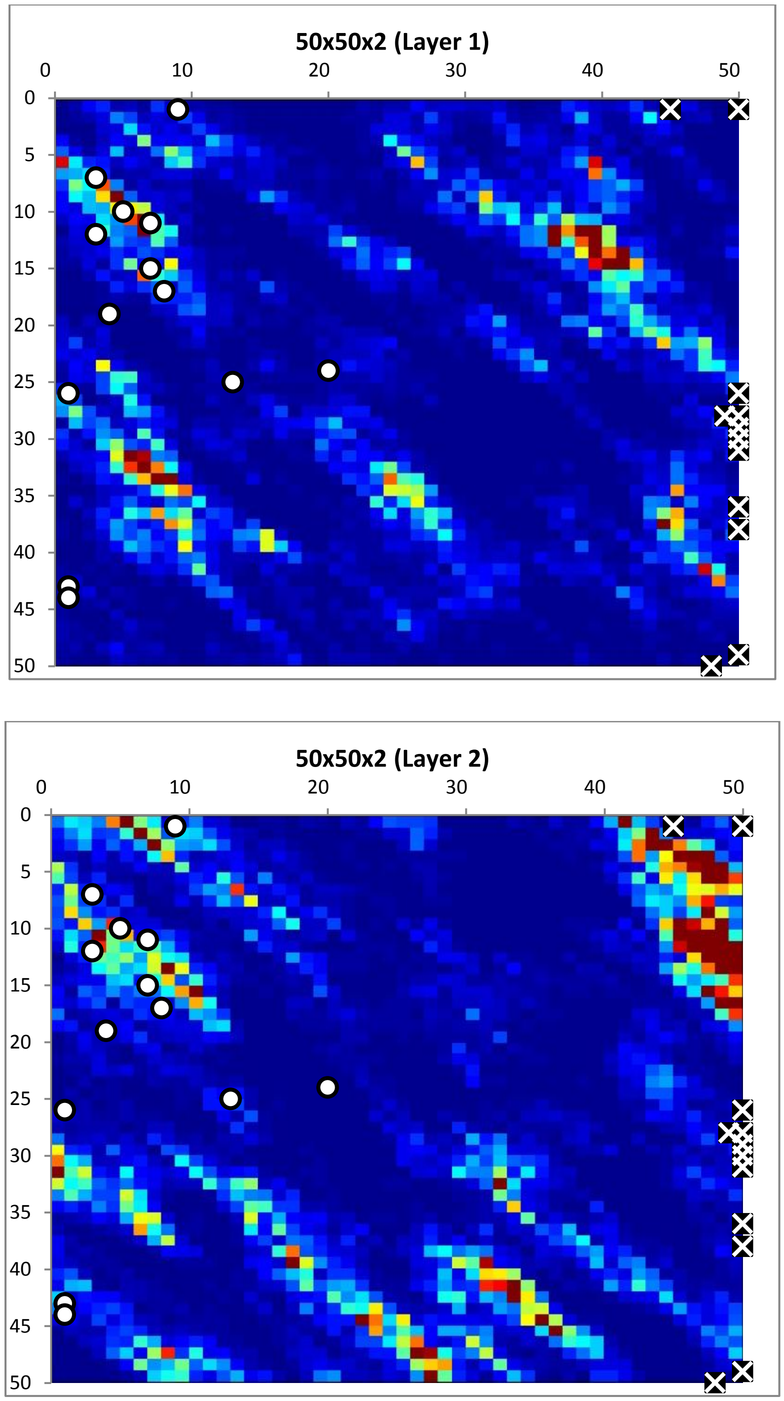


Figure 5.36: Median Solution of CMAES for Case-2a

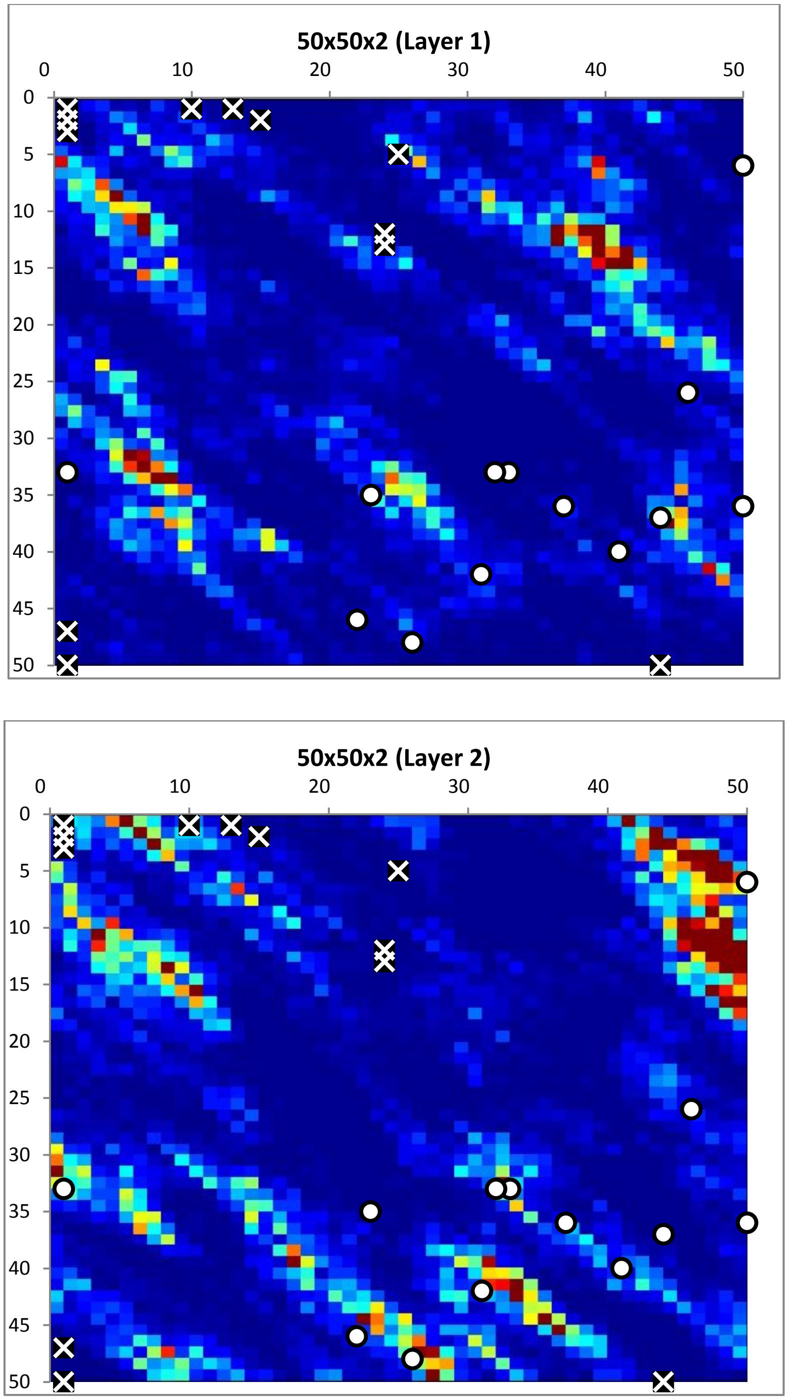


Figure 5.37: Median Solution of DE for Case-2a

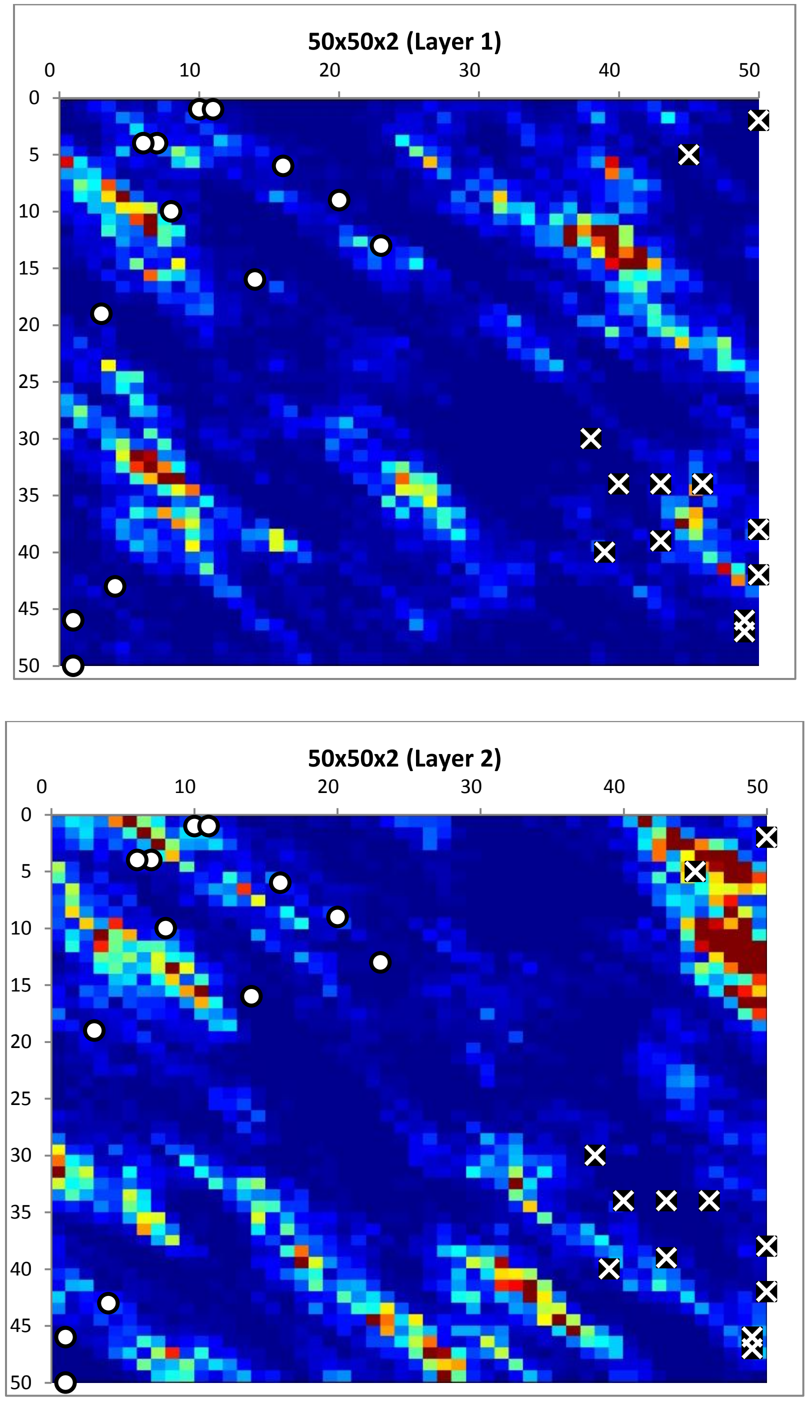


Figure 5.38: Median Solution of IWO for Case-2a

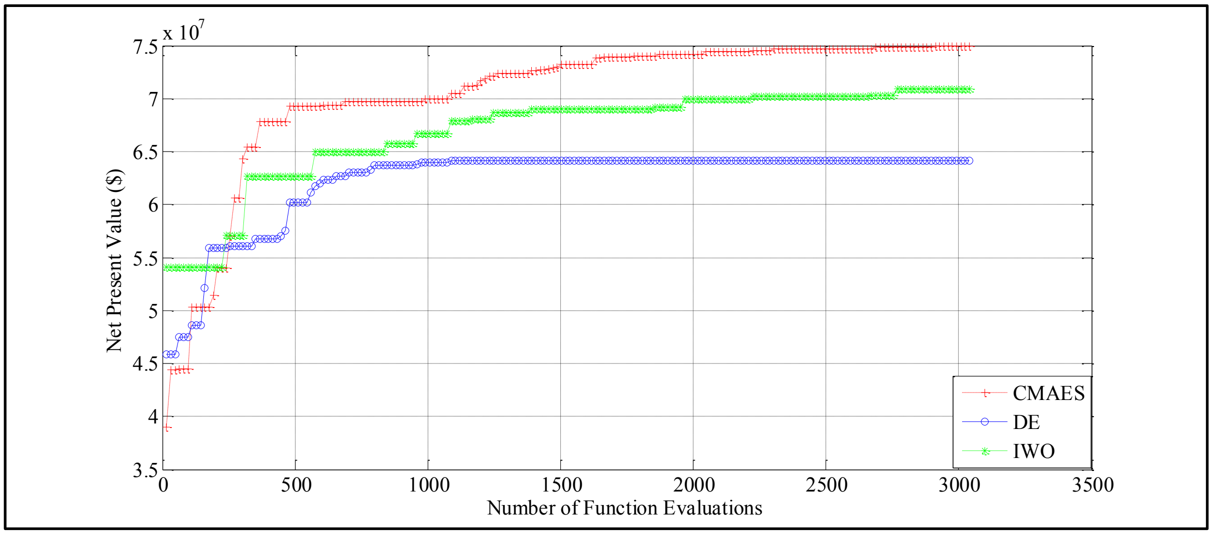


Figure 5.39: Comparison of Worst Solution of CMAES, DE and IWO for Case-2a

Table 5.31: Worst Solution of CMAES for Case-2a

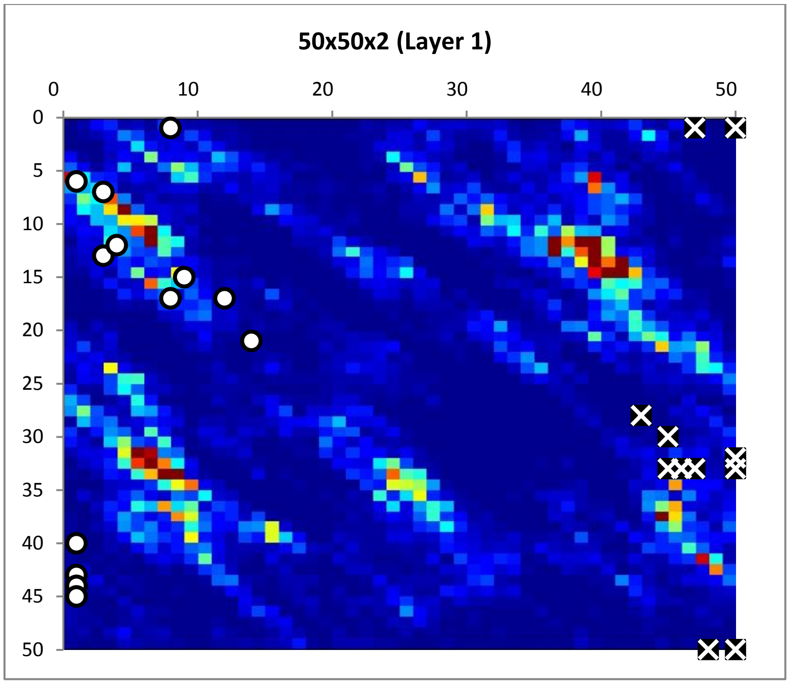
Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	1	43	45	33						
2	1	40	50	32						
3	1	44	50	50						
4	12	17	43	28						
5	3	7	50	32						
6	3	13	48	50						
7	1	6	46	33	4979	342	1620	0.3863	0.0049	**7.5003E+07**
8	8	1	50	33						
9	14	21	45	30						
10	8	17	47	1						
11	1	45	50	1						
12	9	15	47	33						
13	4	12								

Table 5.32: Worst Solution of DE for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	11	12	35	45	6213	1065	1334	0.001	0.0117	**6.4131E+07**
2	50	6	39	49						
3	49	24	3	50						
4	1	37	1	37						
5	24	14	12	27						
6	25	39	26	22						
7	41	38	9	1						
8	50	12	2	28						
9	25	38	1	1						
10	33	50	5	50						
11	50	43	31	25						
12	21	3	25	5						
13	46	32								

Table 5.33: Worst Solution of IWO for Case-2a

Optimized Variables										NPV
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	19	1	10	50	4982	856	1724	0.4362	1	**7.0938E+07**
2	41	2	14	37						
3	32	1	1	41						
4	48	25	3	32						
5	48	50	9	31						
6	28	18	24	10						
7	4	46	1	42						
8	50	12	12	23						
9	50	4	1	49						
10	48	49	8	46						
11	50	29	4	46						
12	9	2	4	42						
13	43	16								



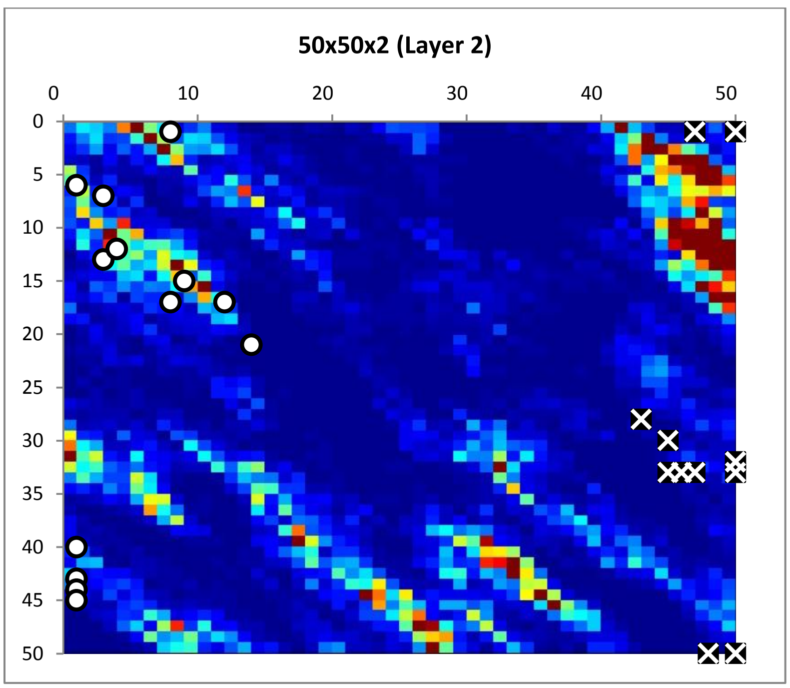


Figure 5.40: Worst Solution of CMAES for Case-2a

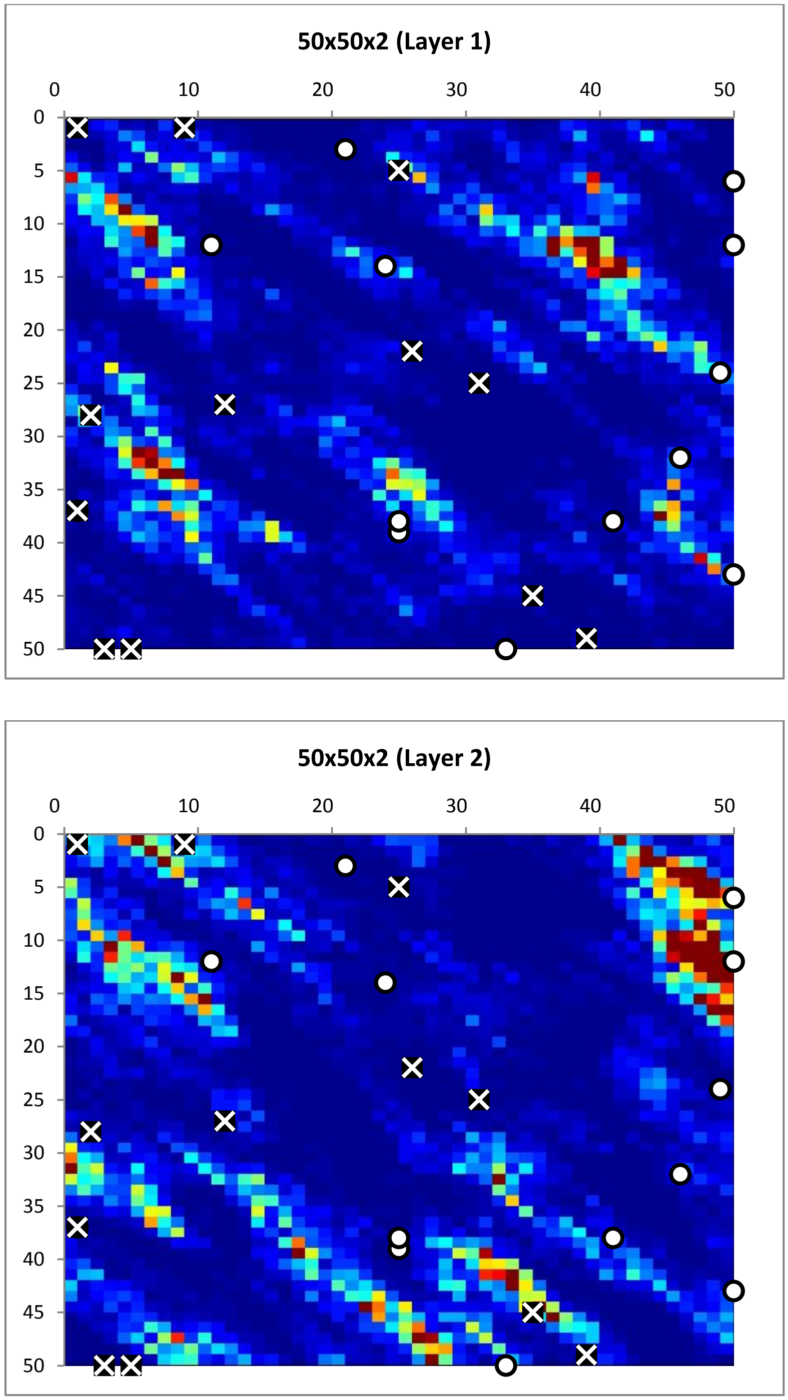
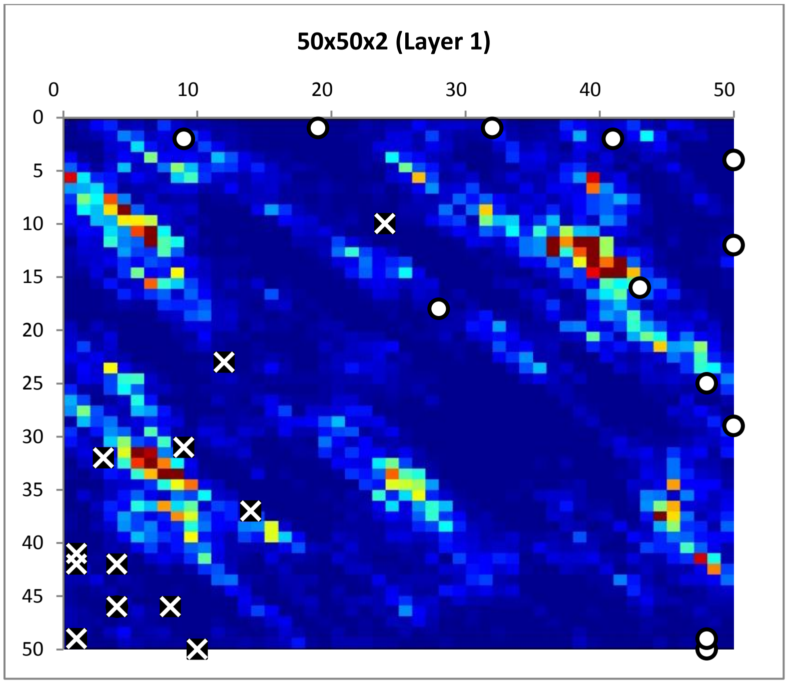


Figure 5.41: Worst Solution of DE for Case-2a



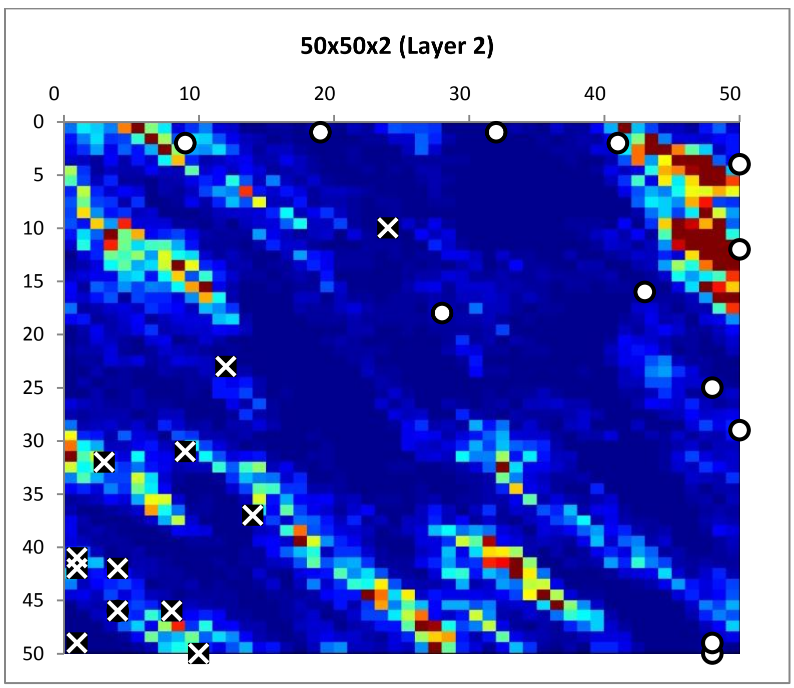


Figure 5.42: Worst Solution of IWO for Case-2a

Discussion

This is a summary of the results presented

NPV

CMAES showed highest values of NPV amongst the three stochastic algorithms for best, median and worst realizations. CMAES is followed by IWO and DE for all realizations.

Convergence

CMAES and IWO showed continuously improving trend with small steps towards the higher values of objective function while DE converges earlier than these two techniques to a lower values of NPV.

Consistency

The three techniques remained almost consistent for this case.

EOR process Selection

The three techniques showed invariable EOR process selection for all the realizations under consideration. The selected EOR process configuration for the highest value of NPV for this case is waterflooding followed by surfactant flooding and then polymer flooding.

Well Placement

Well placement in this optimization problem is significantly influenced by the heterogeneity of the reservoir. The overlapping of wells in some realizations can be resolved by combining the total liquid rate constraint of more than one well in single well if the wells are of the same type (producer). If there is an overlapping of different well types (injector & producer), then the configuration is invalid. In case of clustering of wells in one location, check the minimum well spacing that guarantees the safety of each well. If it is met than that configuration is valid, otherwise not.

The higher values of NPV were obtained when the producers were placed in high permeability zones and injectors followed the heterogeneity of the reservoir.

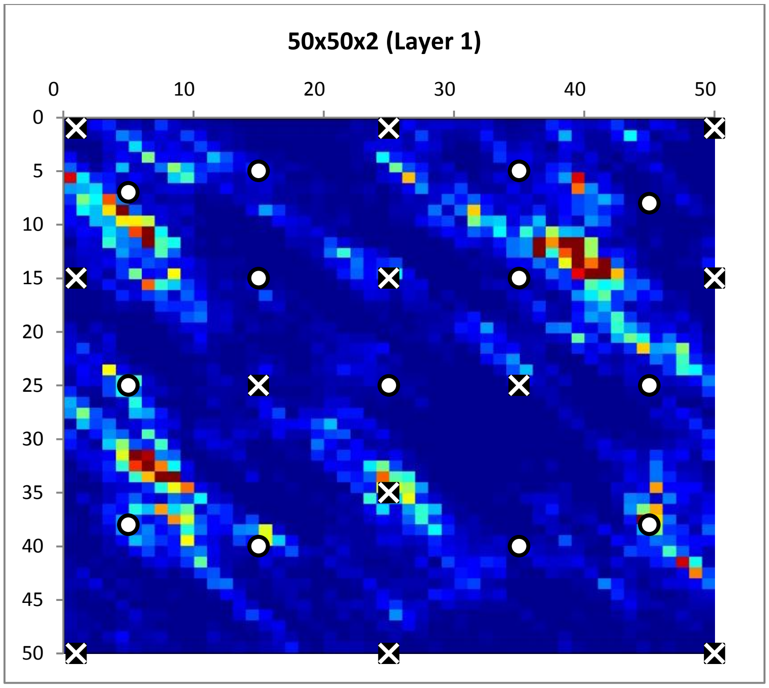
5.5.1.2.2 Case-2b: SP Flooding without Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding without well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic evolutionary algorithms. Table 5.34 shows the input data for this case. Table 5.35 to Table 5.43, and Figs. 5.44 to 5.46 show the results obtained after optimization.

Table 5.34 shows that thirteen (13) producers and twelve (12) injectors were used for this case and their locations are fixed as shown in Fig. 5.43. The surfactant and polymer concentrations in injection wells to be determined is two (2). Including the time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 5.

Table 5.34: Case-2b: SP Flooding without Well Placement Optimization

Production Wells	13
Injection Wells	12
Reservoir Life (days)	10950
Number of Variables	5
Number of Generations	75
Population Size	8
Function Evaluation	600
Number of Realizations	3



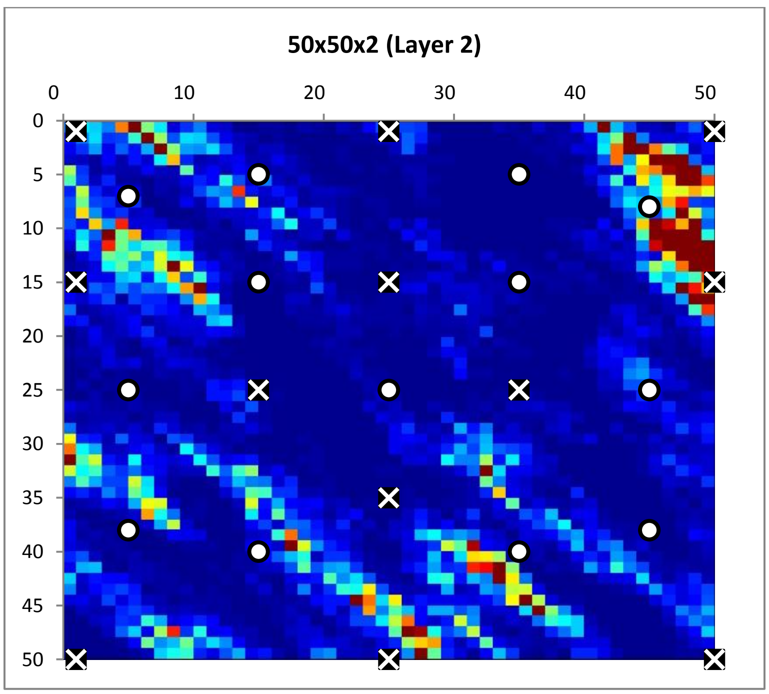


Figure 5.43: Well Locations for Case-2b

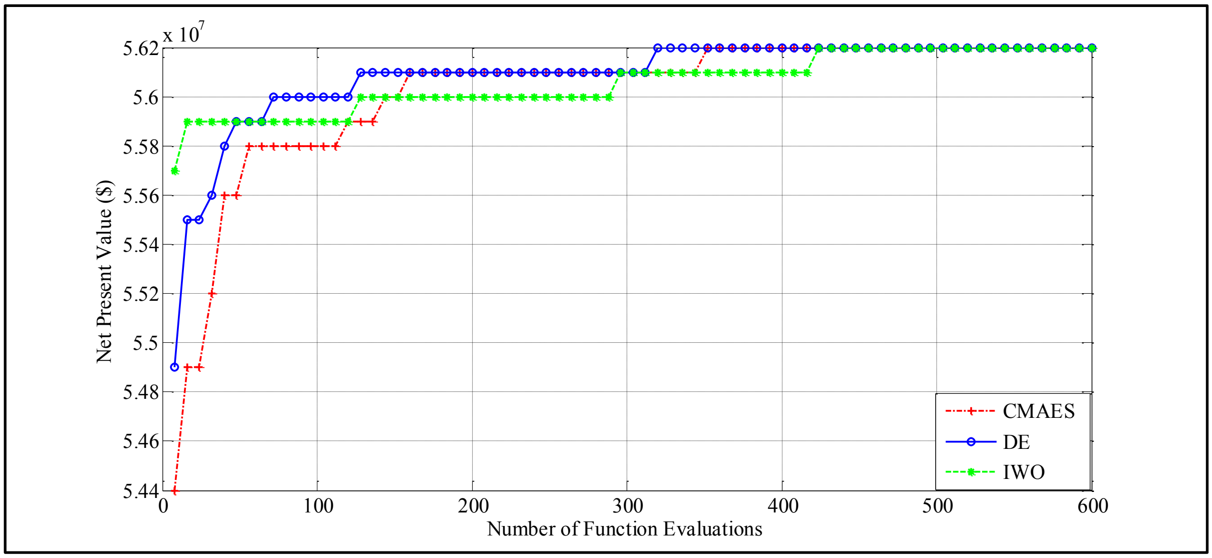


Figure 5.44: Comparison of Best Solution of CMAES and IWO for Case-2b

Table 5.35: Best Solution of CMAES for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables					NPV
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5362	41	1825	0.9061	1	**5.6176E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.36: Best Solution of DE for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5361	58	1787	0.9988	0.9796	**5.6166E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.37: Best Solution of IWO for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	NPV
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5406	20	1825	0.001	1	**5.6164E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

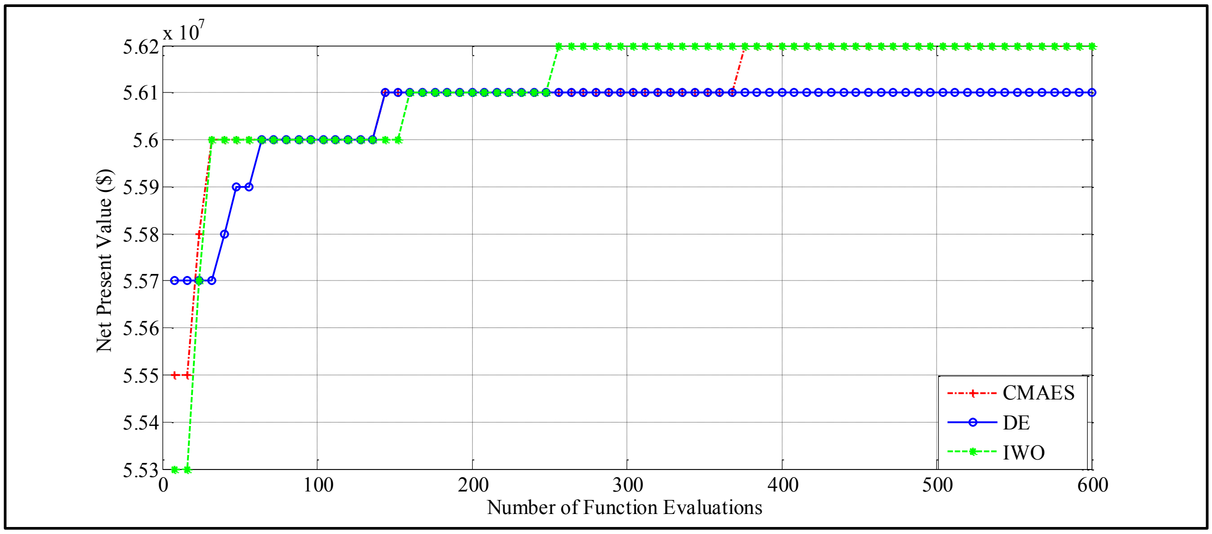


Figure 5.45: Comparison of Median Solution of CMAES, DE and IWO for Case-2b

Table 5.38: Median Solution of CMAES for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables					NPV
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15						
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50	5347	55	1825	0.8560	0.9917	**5.6167E+07**
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.39: Median Solution of DE for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5331	47	604	0.98	1	**5.6077E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.40: Median Solution of IWO for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5428	0	1825	0	1	**5.6164E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

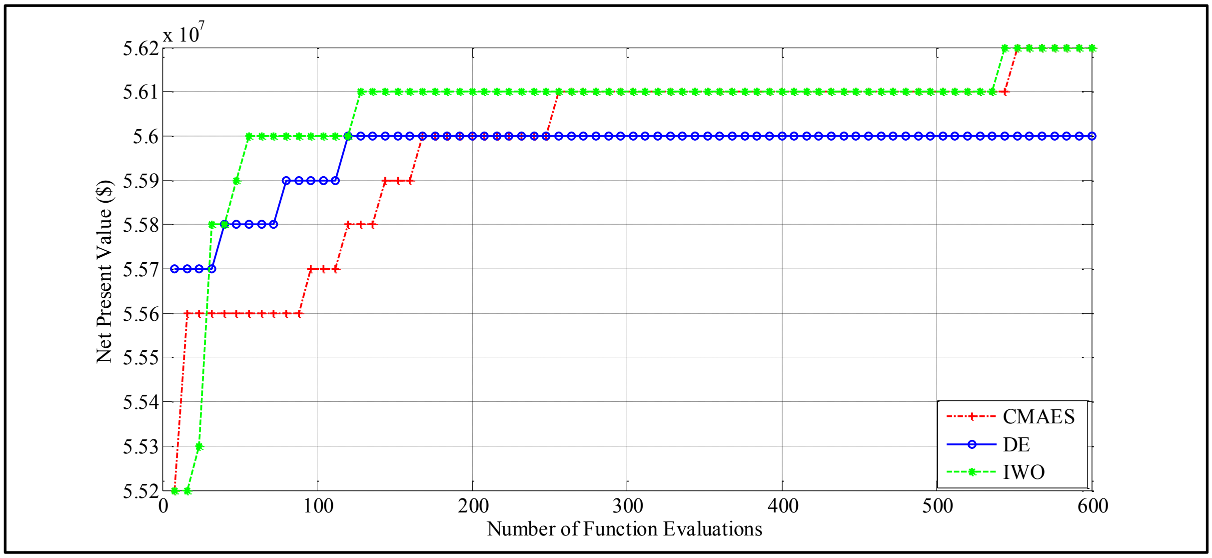


Figure 5.46: Comparison of Worst Solution of CMAES, DE and IWO for Case-2b

Table 5.41: Worst Solution of CMAES for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables					NPV
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5243	185	1825	0.001	1	**5.6152E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.42: Worst Solution of DE for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5602	188	230	0.5591	0.9851	**5.6025E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.43: Worst Solution of IWO for Case-2b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**NPV**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	**$**
1	25	25	25	15	5360	86	1767	0.001	1	**5.6161E+07**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Discussion

This is a summary of the results presented

NPV

All the three stochastic algorithms (CMAES, IWO and DE) showed almost the same values of NPV for the best, median and worst realizations with DE showing the NPV values slightly lower than the CMAES and IWO.

Convergence

CMAES and IWO showing similar continuously improving trend of convergence while DE converges earlier than these two techniques.

Consistency

The three techniques remained almost consistent for this case.

EOR process Selection

The three techniques showed invariable EOR process selection for best, median and worst realizations except the median realization of IWO which selected water flooding followed by polymer flooding without surfactant flooding. The selected EOR process configuration for this case is waterflooding followed by surfactant flooding and then polymer flooding.

5.5.1.2.3 Comparison of Case-2a, Case-2b and Waterflooding

A base case having fixed well locations with simple waterflooding was run and compared with SP flooding process with well placement optimization (Case-2a) and SP flooding process without well placement optimization (Case-2b). Well placement configuration for the base case and Case-2b remains the same. Table 5.44, Figs. 5.47 and 5.48 showed the summary of Case-2a, Case-2b and waterflooding for best, median and worst realizations for Reservoir Model-2. The incremental NPV values are calculated by comparing each of Case-2a and Case-2b with waterflooding.

It is evident from the results that there is an increase in the NPV after the implementation of stochastic optimization techniques. An increase of around 3.21% to 3.48% is observed when SP flooding is optimized without well placement optimization. However, SP flooding with well placement optimization showed increase in NPV in the range of about 18.14% to 44.06%.

Table 5.44: Comparison of Case2a, Case-2b and Waterflooding

Reservoir Model	Stochastic Technique	Solution Type	SP Flooding with WPO (Case-2a)	SP Flooding without WPO (Case-2b)	Water flooding	Incremental NPV (Case-2a)	Incremental NPV (Case-2b)
			million $	million $	million $	%	%
Reservoir Model-2	CMAES	Best	78.20	56.18	54.29	44.06	3.48
		Median	70.39	56.17	54.29	29.67	3.47
		Worst	75.00	56.15	54.29	38.17	3.44
	DE	Best	70.39	56.17	54.29	29.67	3.47
		Median	69.99	56.08	54.29	28.93	3.30
		Worst	64.13	56.03	54.29	18.14	3.21
	IWO	Best	72.95	56.16	54.29	34.38	3.46
		Median	72.57	56.16	54.29	33.68	3.46
		Worst	70.94	56.16	54.29	30.68	3.46

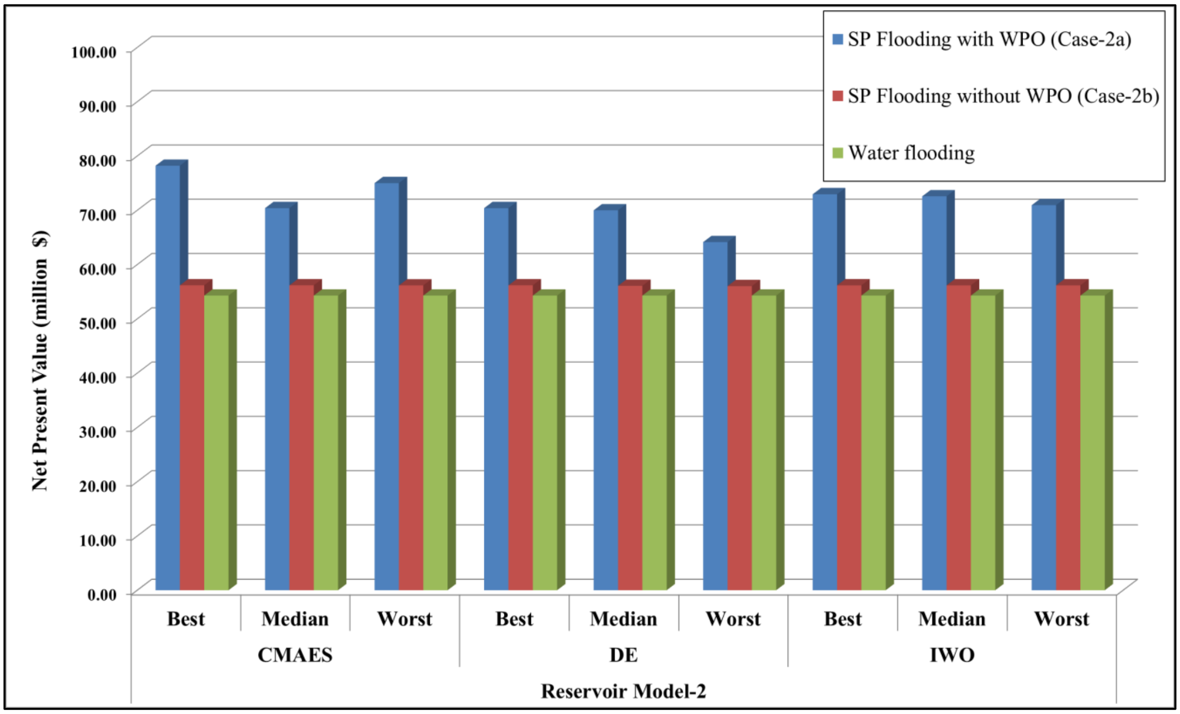


Figure 5.47: Comparison of Case2a, Case-2b and Waterflooding

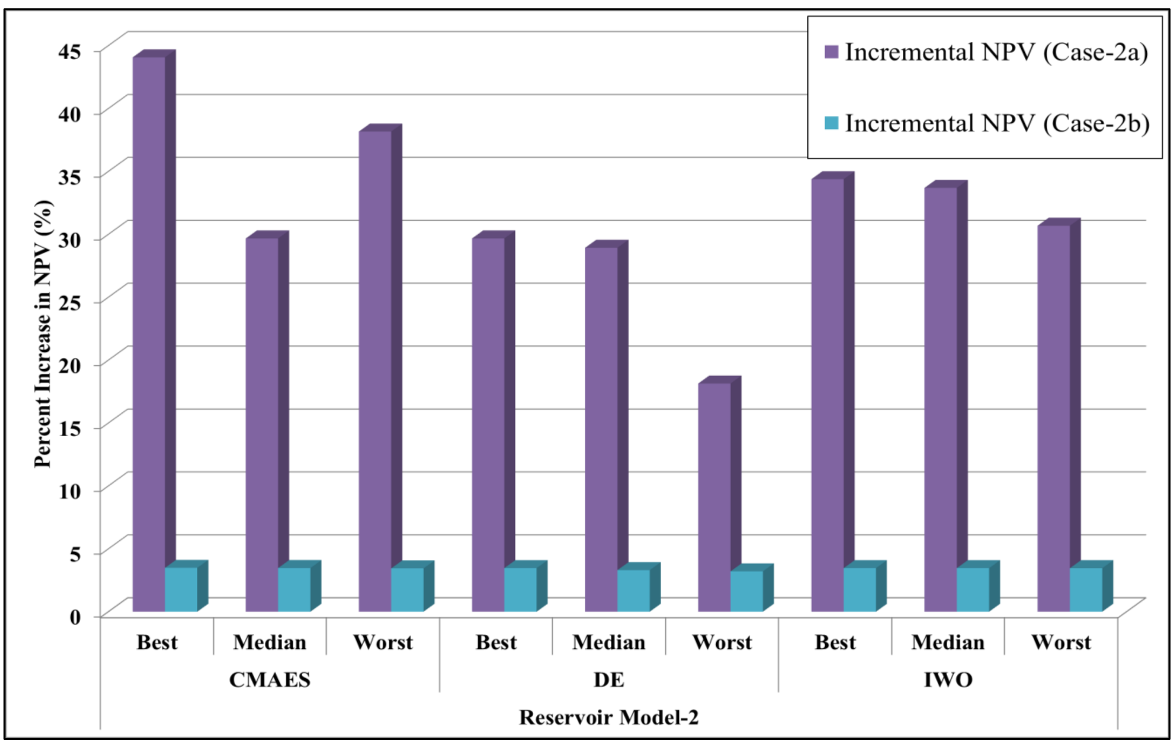


Figure 5.48: Incremental NPV from Case-2a, Case-2b

5.5.2 Ultimate Recovery

Ultimate recovery is the maximum amount of hydrocarbon we can extract from a hydrocarbon reservoir. It can be given by

$$UR = Original\ Oil\ in\ Place\ x\ Ultimate\ Recovery\ Factor \tag{5.1}$$

The main objective of enhanced oil recovery mechanisms is to increase the 'Ultimate Recovery Factor' to unity such that we can produce the last drop of oil economically.

Optimization of SP flooding and well placement was done for Reservoir Model-1 and Model-2 using stochastic optimization algorithms. The objective function in this case was ultimate recovery. The results of the optimization are discussed in this section.

5.5.2.1 Case-3: UR Optimization for Reservoir Model-1 (Channeled Reservoir)

Optimization study for Reservoir Model-1 is performed using the three stochastic optimization discussed in Section 3.1.

The optimization study is carried out using the following two subcases

1. Optimization of surfactant-polymer flooding with well placement optimization (See section 5.5.2.1.1).
2. Optimization of surfactant-polymer flooding without well placement optimization (See section 5.5.2.1.2).

In each of these subsections, three realizations of the three optimization algorithms (CMAES, DE and IWO) were generated and the Best, Median and Worst solutions were selected for analysis of performance. Furthermore, Section 5.5.2.1.3 compares the results of Sections 5.5.2.1.1 and 5.5.2.1.2.

5.5.2.1.1 Case-3a: SP Flooding with Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding with well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic optimization algorithms. Table 5.45 shows the input data for this case. Table 5.46 to Table 5.54, and Figs. 5.49 to 5.60 show the results obtained after optimization.

Table 5.45 shows that ten (10) producers and eight (8) injectors were used for this case making a total of eighteen (18) wells. The number of (x,y) well locations to be determined is thirty-six (36) while the surfactant and polymer concentrations in injection wells to be determined is two (2). Including time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters 41.

Table 5.45: Case-3a: SP Flooding with Well Placement Optimization

Production Wells	10
Injection Wells	8
Reservoir Life (days)	73000
Number of Variables	41
Number of Generations	150
Population Size	15
Function Evaluation	2250
Number of Realizations	3

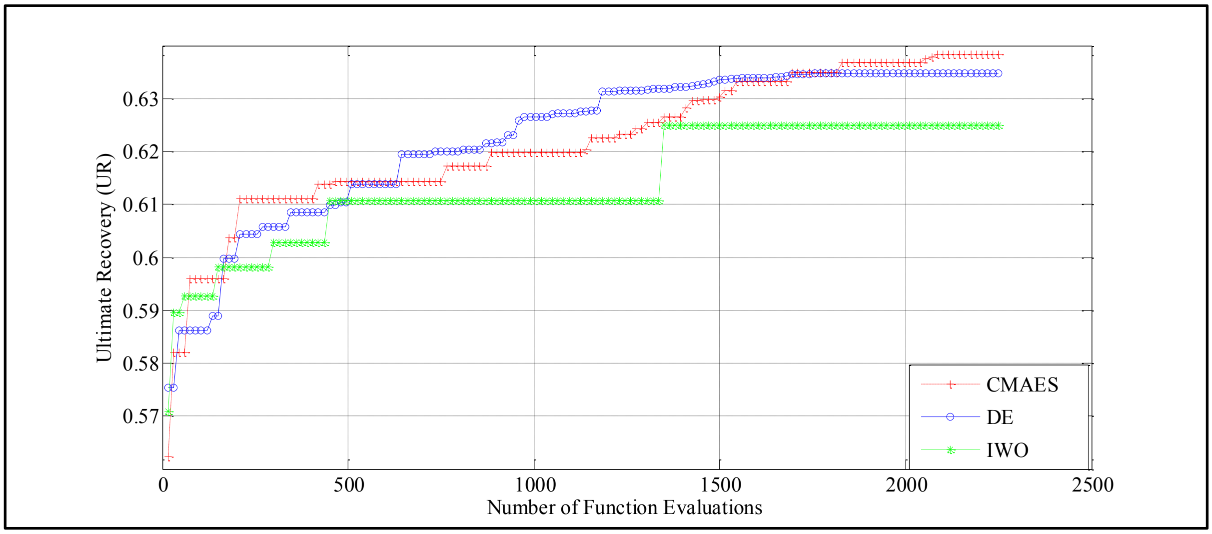


Figure 5.49: Comparison of Best Solution of CMAES, DE and IWO for Case-3a

Table 5.46: Best Solution of CMAES for Case-3a

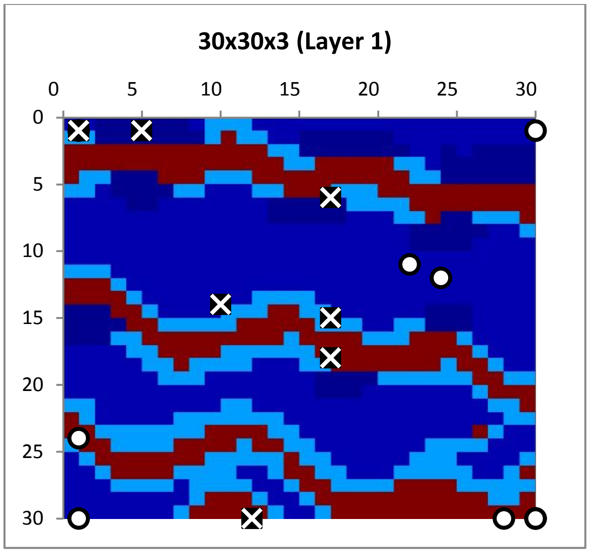
<table>
<tr><th colspan="10">Optimized Variables</th><th rowspan="2">UR</th></tr>
<tr><th>No.</th><th colspan="2">Production Wells</th><th colspan="2">Injection Wells</th><th>Duration for Water Flooding</th><th>Duration for Surfactant Flooding</th><th>Duration for Polymer Flooding</th><th>Surfactant Conc.</th><th>Polymer Conc.</th></tr>
<tr><th></th><th>x</th><th>y</th><th>x</th><th>y</th><th>days</th><th>days</th><th>days</th><th>lb/STB</th><th>lb/STB</th><th></th></tr>
<tr><td>1</td><td>30</td><td>1</td><td>17</td><td>18</td><td rowspan="10">2264</td><td rowspan="10">1047</td><td rowspan="10">1825</td><td rowspan="10">1.00</td><td rowspan="10">0.85</td><td rowspan="10">0.6383</td></tr>
<tr><td>2</td><td>28</td><td>30</td><td>5</td><td>1</td></tr>
<tr><td>3</td><td>22</td><td>11</td><td>17</td><td>6</td></tr>
<tr><td>4</td><td>1</td><td>24</td><td>10</td><td>14</td></tr>
<tr><td>5</td><td>1</td><td>30</td><td>17</td><td>15</td></tr>
<tr><td>6</td><td>30</td><td>30</td><td>1</td><td>1</td></tr>
<tr><td>7</td><td>30</td><td>30</td><td>12</td><td>30</td></tr>
<tr><td>8</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>9</td><td>24</td><td>12</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>10</td><td>30</td><td>30</td></tr>
</table>

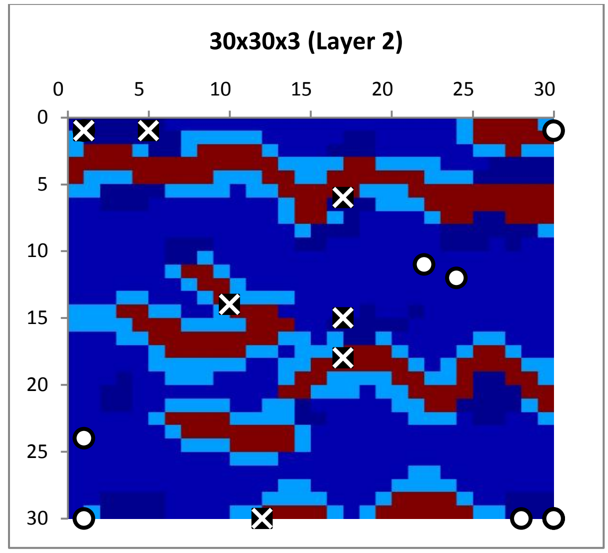
Table 5.47: Best Solution of DE for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	19	6	30	8	2190	820	1697	1.00	0.99	**0.6348**
2	30	30	20	18						
3	30	26	11	17						
4	24	30	5	5						
5	25	25	30	4						
6	30	1	1	6						
7	7	29	8	8						
8	28	26	30	1						
9	15	1								
10	1	30								

Table 5.48: Best Solution of IWO for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	29	1	12	5	4069	1015	1825	0.55	1.00	**0.6250**
2	1	29	14	3						
3	1	10	29	19						
4	5	25	18	30						
5	1	1	15	16						
6	2	30	16	6						
7	4	29	29	7						
8	29	24	26	9						
9	10	30								
10	2	24								





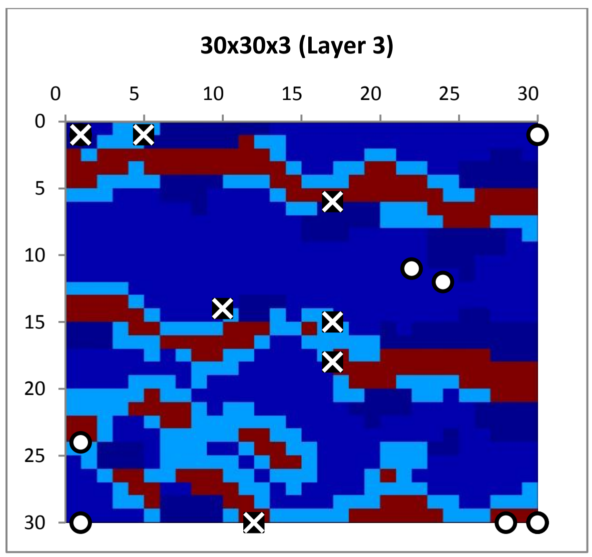


Figure 5.50: Best Solution of CMAES for Case-3a

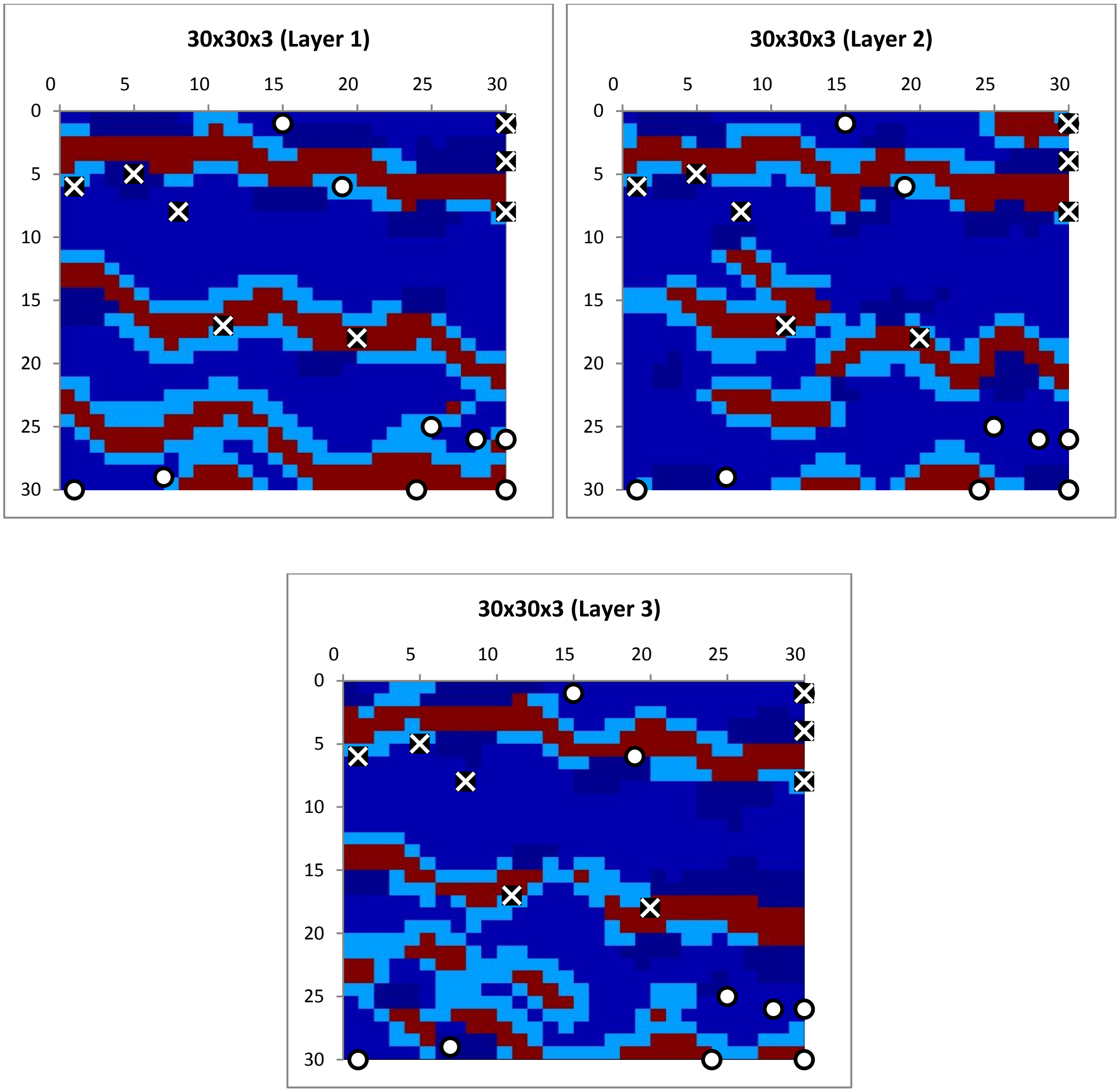


Figure 5.51: Best Solution of DE for Case-3a

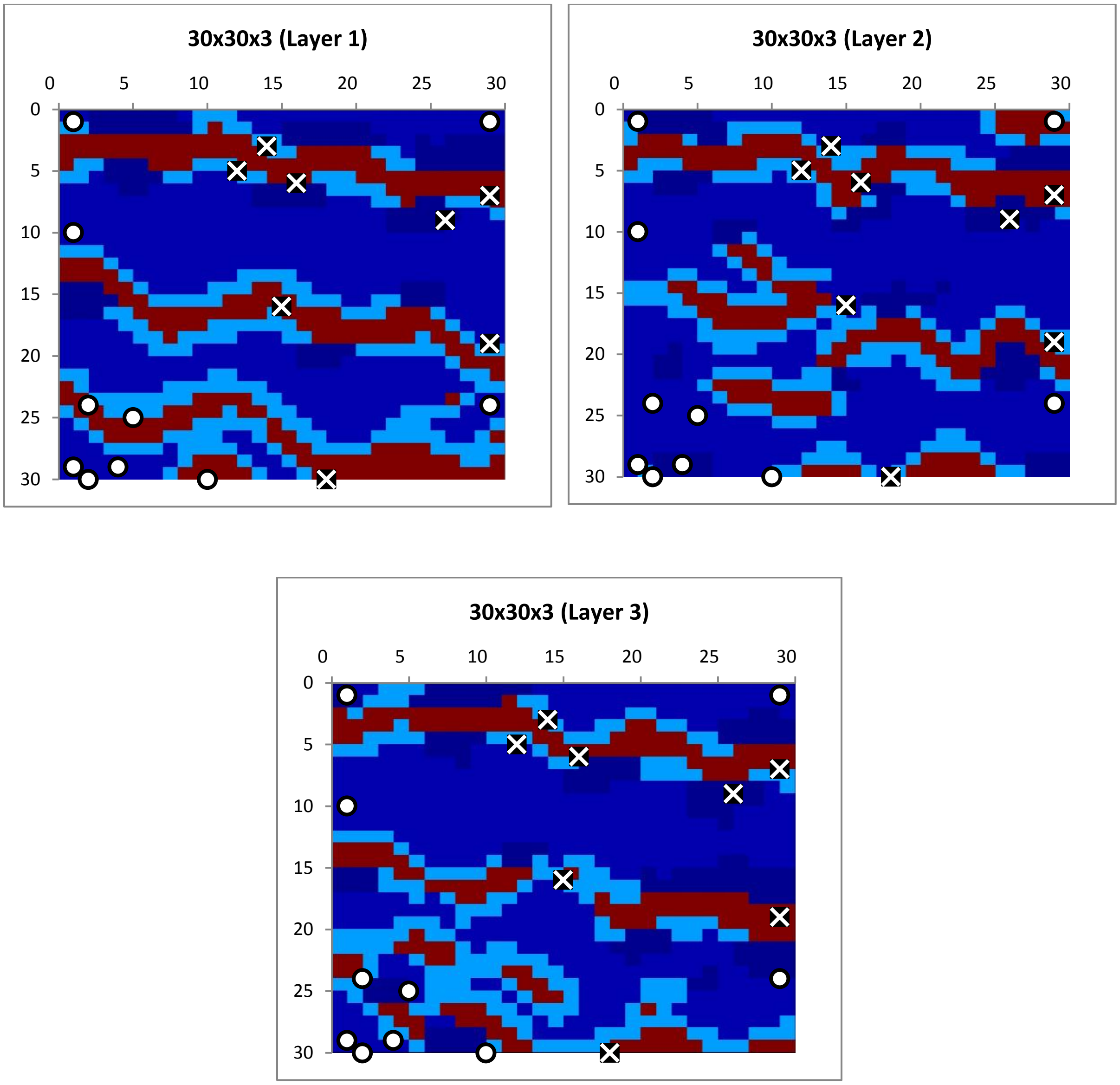


Figure 5.52: Best Solution of IWO for Case-3a

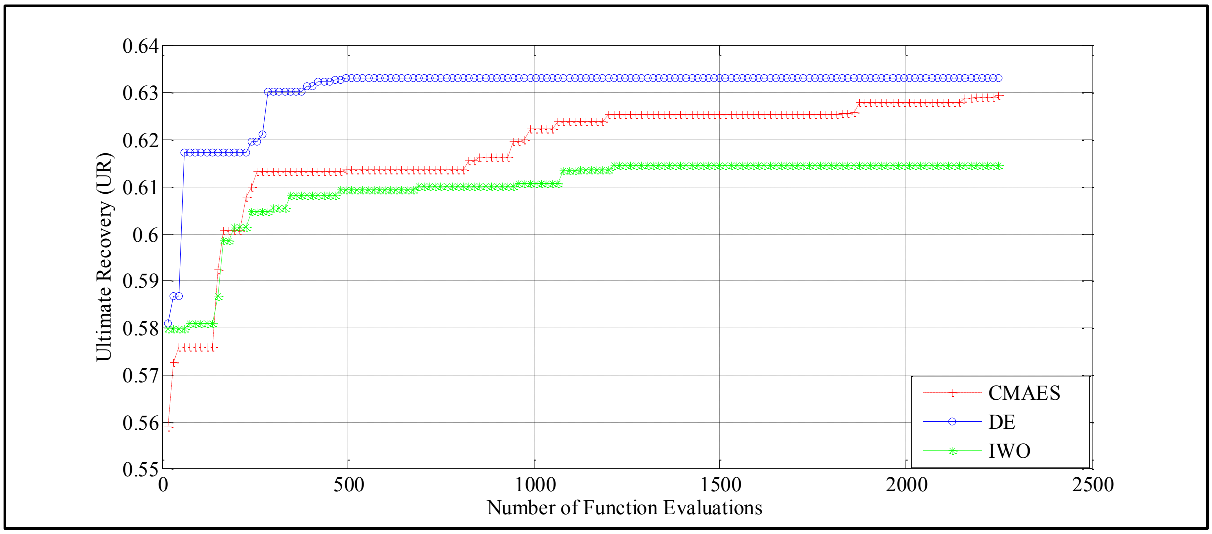


Figure 5.53: Comparison of Median Solution of CMAES, DE and IWO for Case-3a

Table 5.49: Median Solution of CMAES for Case-3a

Optimized Variables										**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	1	1	30	1	2190	189	1825	0.68	0.70	**0.6295**
2	6	25	19	9						
3	12	30	23	7						
4	1	25	30	8						
5	1	25	20	20						
6	30	30	1	13						
7	6	11	30	9						
8	24	27	30	9						
9	2	30								
10	19	29								

Table 5.50: Median Solution of DE for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	1	22	6	3	2207	4	1823	0.001	0.93	**0.6332**
2	26	21	28	23						
3	30	2	3	3						
4	3	26	30	7						
5	7	2	2	3						
6	25	29	17	18						
7	3	28	11	25						
8	30	30	18	8						
9	30	29								
10	30	17								

Table 5.51: Median Solution of IWO for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	1	25	25	4	6214	522	1651	0.92	0.90	**0.6145**
2	14	30	30	5						
3	1	22	30	1						
4	18	20	14	2						
5	23	30	27	8						
6	5	27	24	14						
7	1	13	29	5						
8	18	28	17	5						
9	25	24								
10	1	22								

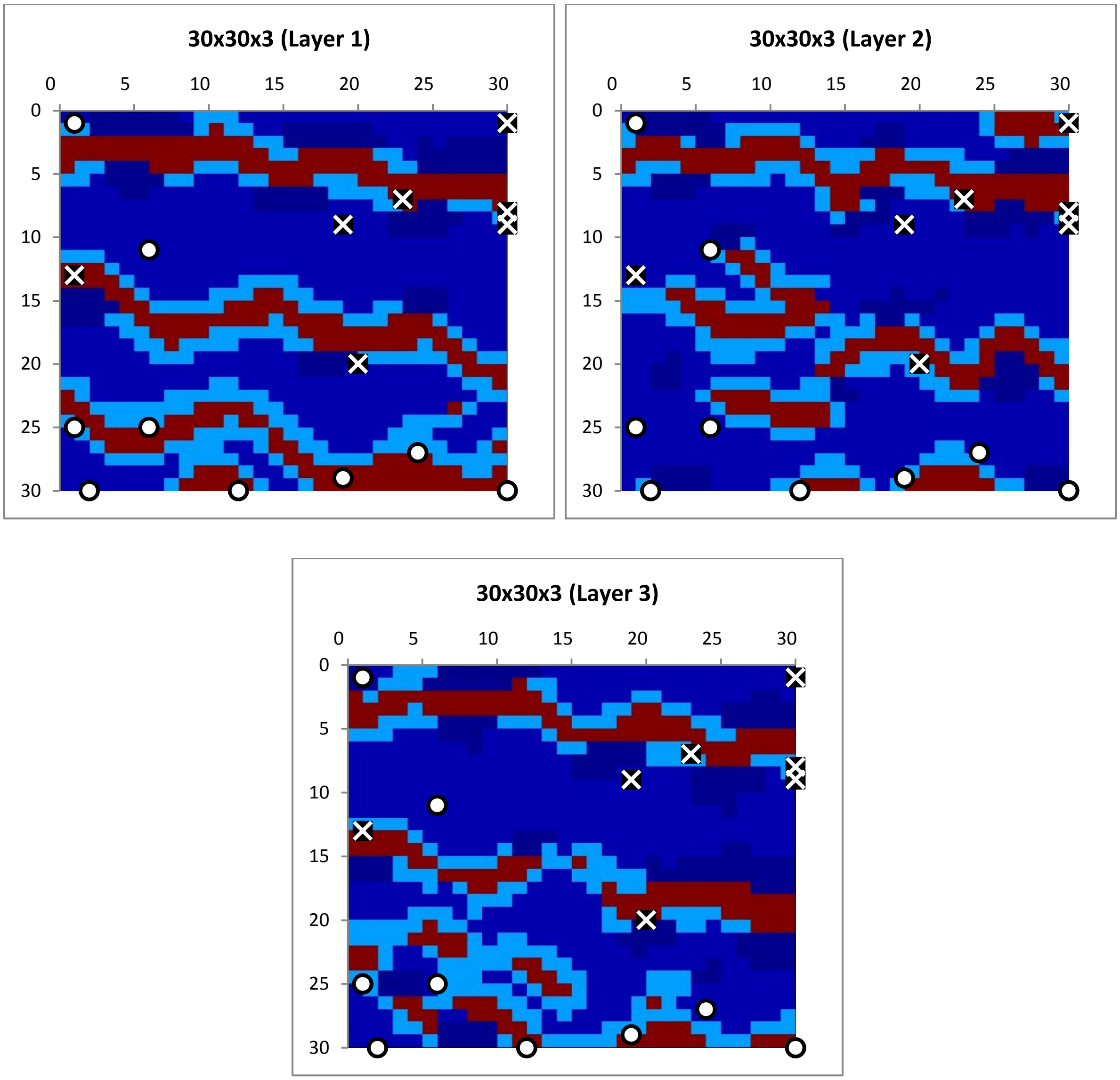


Figure 5.54: Median Solution of CMAES for Case-3a

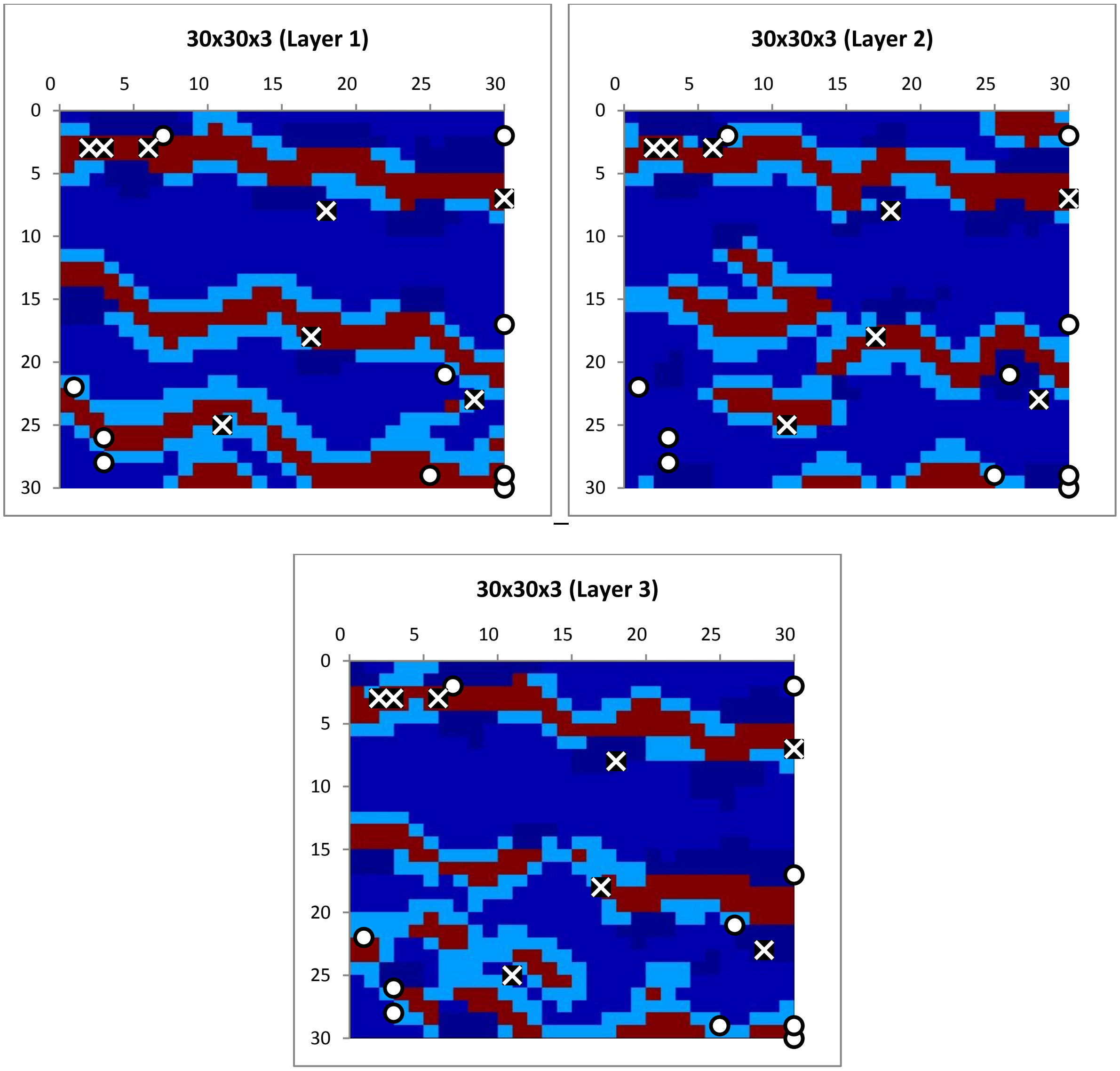


Figure 5.55: Median Solution of DE for Case-3a

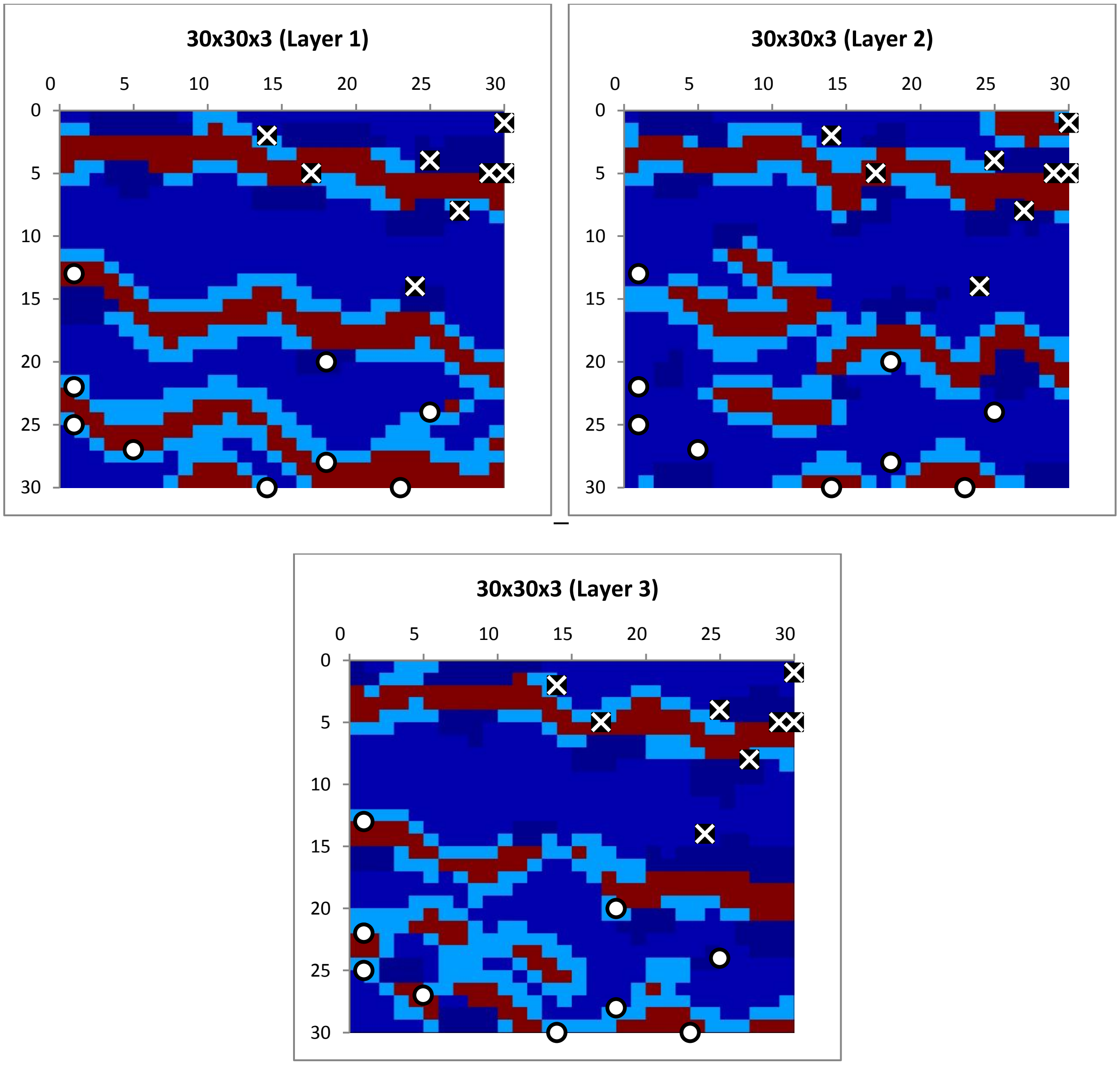


Figure 5.56: Median Solution of IWO for Case-3a

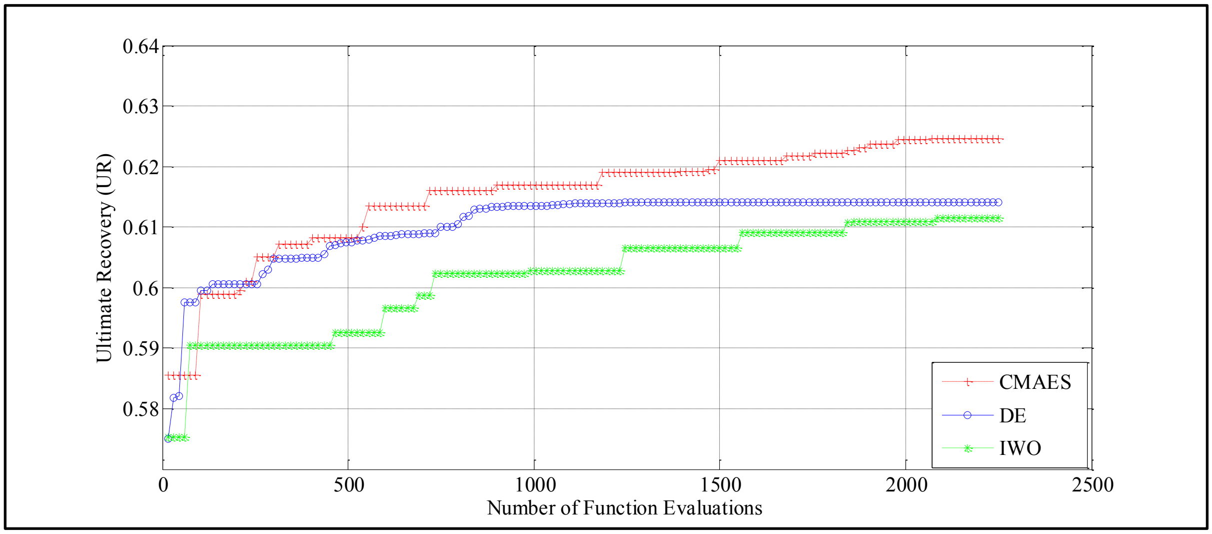


Figure 5.57: Comparison of Worst Solution of CMAES, DE and IWO for Case-3a

Table 5.52: Worst Solution of CMAES for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	23	19	4	1	5727	1095	418	0.87	0.30	**0.6246**
2	9	30	29	8						
3	1	30	12	11						
4	30	1	6	2						
5	30	30	23	25						
6	30	30	3	1						
7	22	13	9	1						
8	1	24	16	30						
9	30	30								
10	30	30								

Table 5.53: Worst Solution of DE for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	5	3	9	1	6051	137	1821	0.01	0.42	**0.6141**
2	1	1	1	30						
3	23	4	26	10						
4	11	15	30	30						
5	6	16	18	22						
6	30	1	11	30						
7	30	13	29	30						
8	30	6	5	20						
9	10	30								
10	23	2								

Table 5.54: Worst Solution of IWO for Case-3a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	22	1	10	25	3843	0	1825	0	0.7868	**0.6115**
2	22	6	1	14						
3	20	4	29	20						
4	11	15	8	16						
5	30	6	28	28						
6	2	29	30	30						
7	13	20	16	25						
8	1	27	4	5						
9	15	30								
10	30	1								

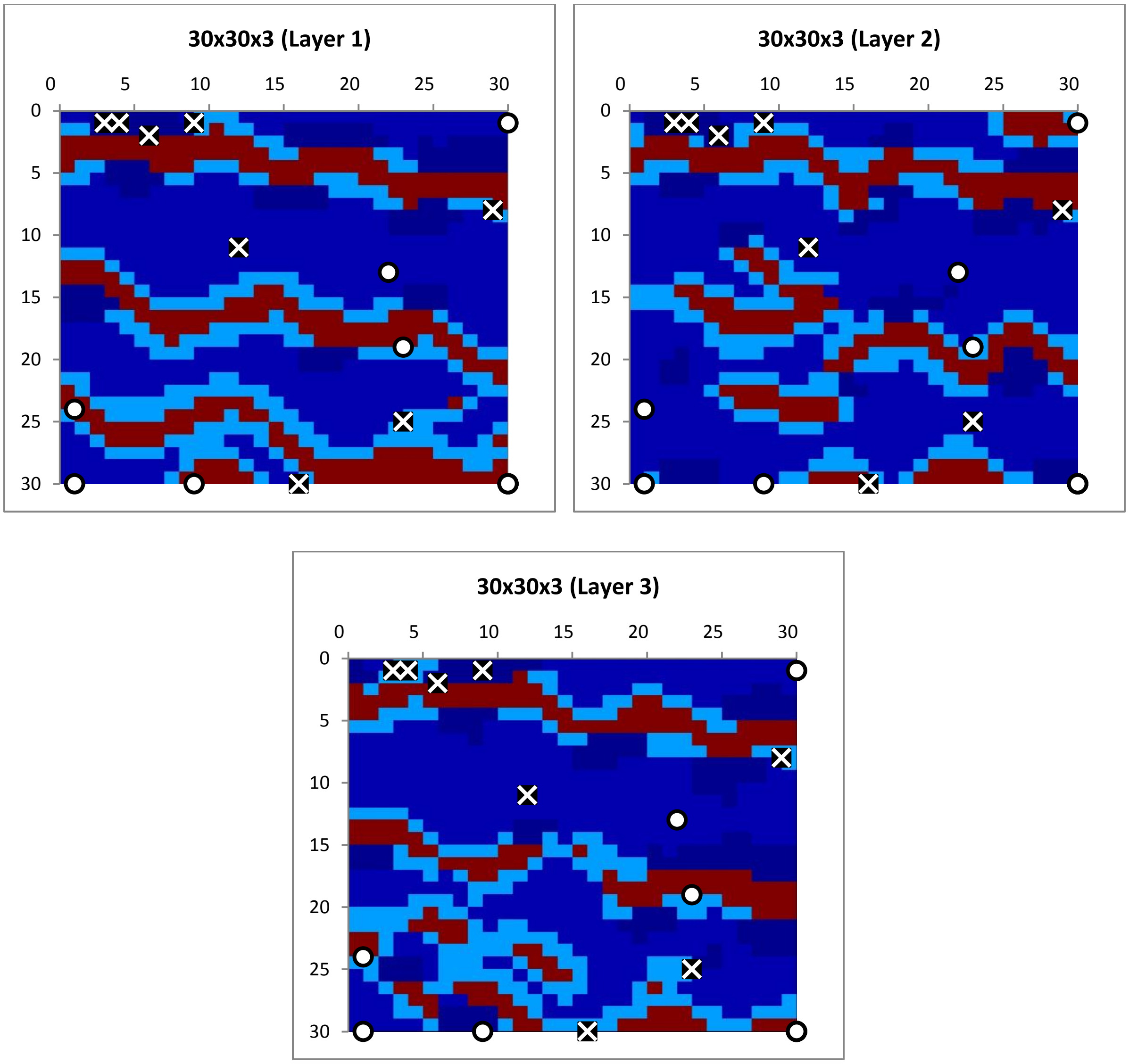


Figure 5.58: Worst Solution of CMAES for Case-3a

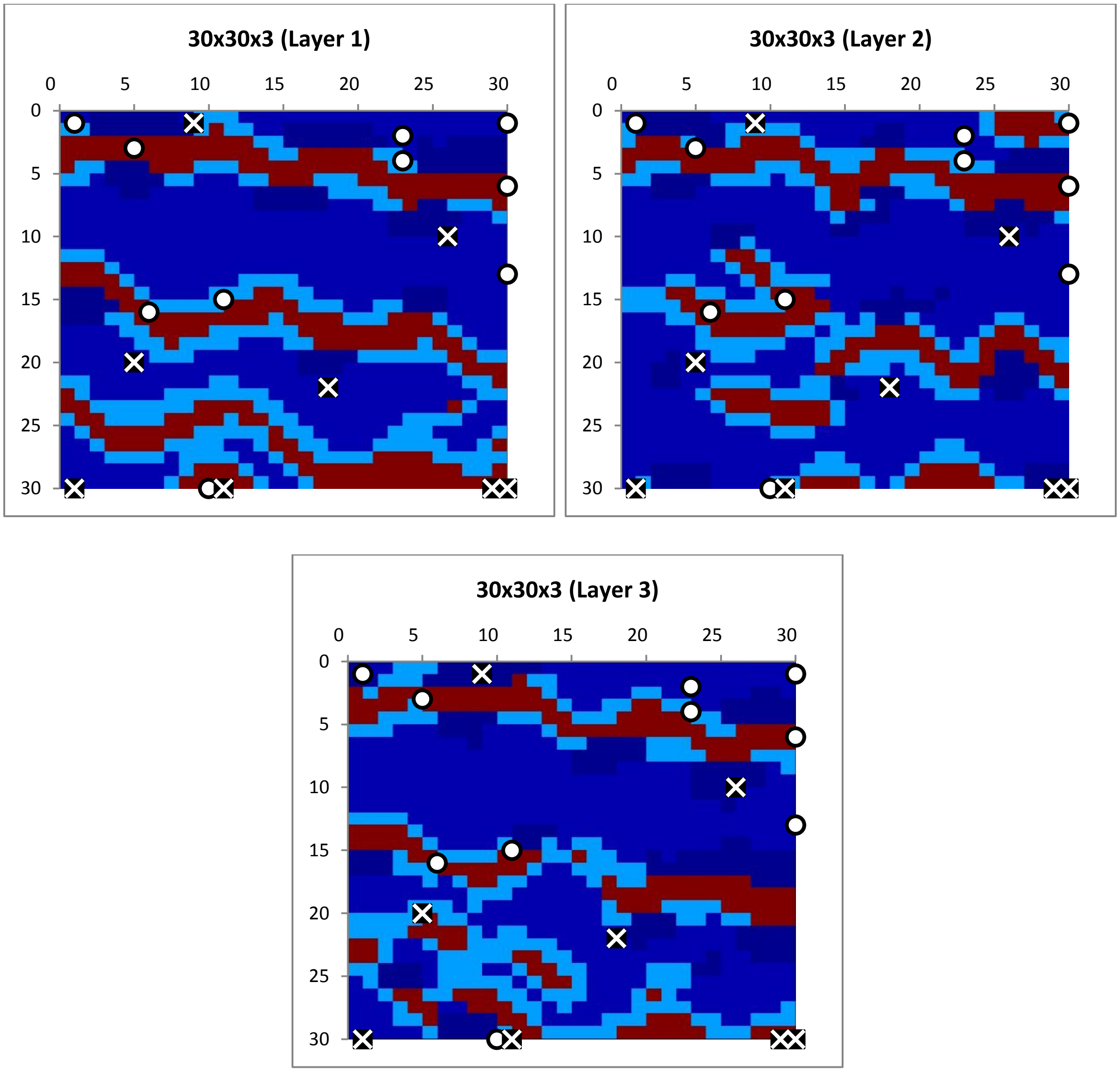


Figure 5.59: Worst Solution of DE for Case-3a

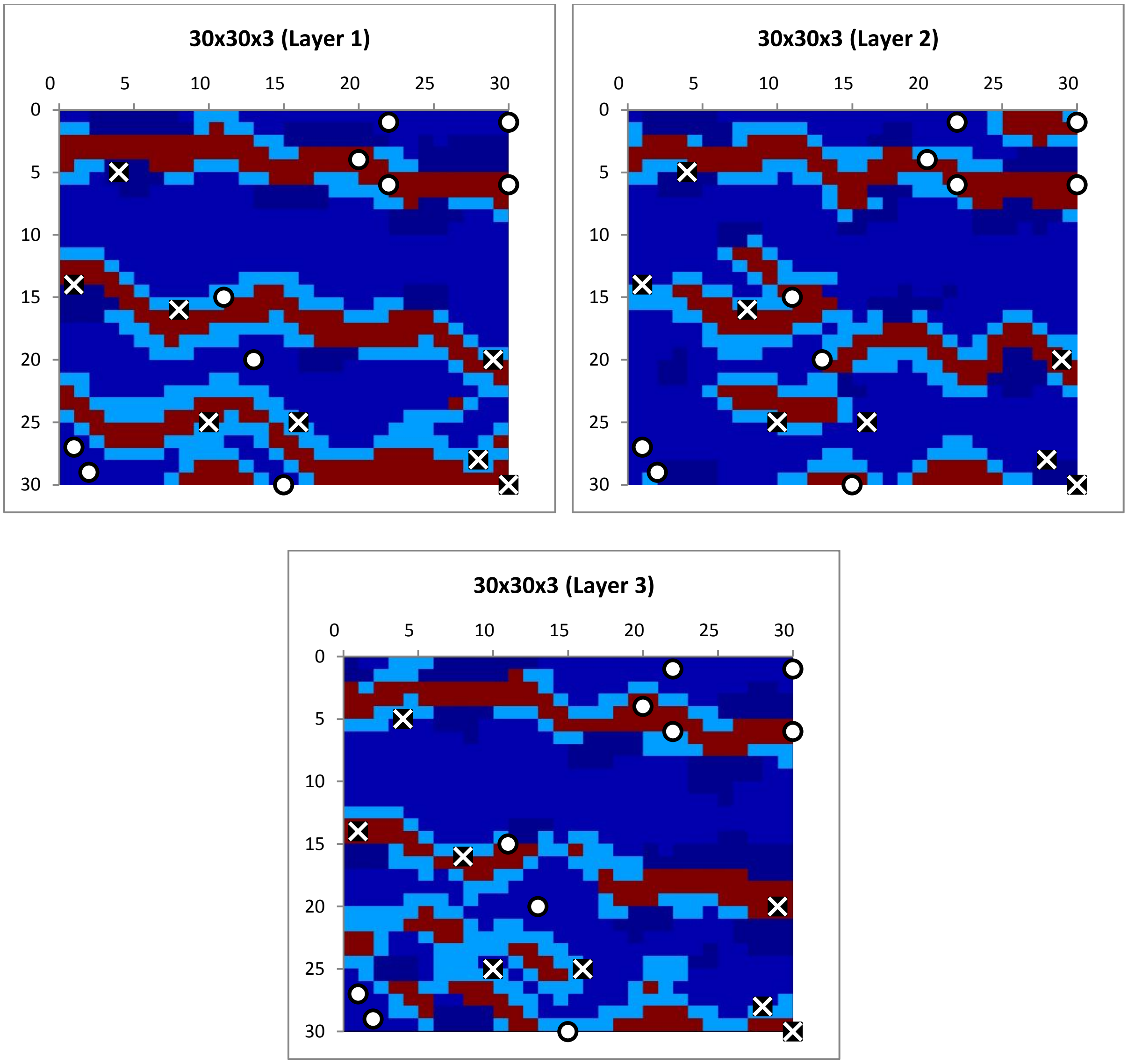


Figure 5.60: Worst Solution of IWO for Case-3a

Discussion

This is a summary of the results presented

UR

CMAES showed highest values of UR amongst the three stochastic algorithms for best and worst realizations which is followed by DE in these two realizations. IWO resulted in the lowest UR values in all three realizations.

Convergence

For the best realization, all three stochastic algorithms showed continuous improvement with small steps towards the optimized solution. However, overall CMAES showed higher tendency of convergence to a better optimized solution than DE and IWO.

Consistency

The three techniques remained almost consistent for this case.

EOR process Selection

The three techniques showed invariable EOR process selection for best, median and worst realizations with the exception of IWO for worst realization which showed waterflooding followed by polymer flooding with no surfactant flooding. However the selected EOR process configuration for the highest value of UR for this case is waterflooding followed by surfactant flooding and then polymer flooding.

Well Placement

The conclusion from the well placement pattern for all the three stochastic techniques is different for the objective of achieving high ultimate recovery values. For CMAES, the high UR values are obtained when the injectors and producers are evenly placed in medium permeability zones. This will help to avoid early water breakthrough and improve the sweep efficiency.

Similarly, DE and IWO showed that higher values of UR can be achieved by placing majority of the injectors and producers in high permeability zones.

The overlapping of wells in some realizations can be resolved by combining the total liquid rate constraint of more than one well in single well if the wells are of the same type (producer). If there is an overlapping of different well types (injector & producer), then the configuration is invalid. In case of clustering of wells in one location, check the minimum well spacing that guarantees the safety of each well. If it is met than that configuration is valid, otherwise not.

It is also evident from the results that higher UR can be achieved if injectors and producers are placed uniformly throughout the reservoir keeping in view the high and low permeability zones.

5.5.2.1.2 Case-3b: SP Flooding without Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding without well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic optimization algorithms. Table 5.55 shows the input data for this case. Table 5.56 to Table 5.64, and Figs. 5.61 to 5.64 show the results obtained after optimization.

Table 5.55 shows that ten (10) producers and eight (8) injectors were used for this case and their locations are fixed as shown in Fig. 5.61. The surfactant and polymer concentrations in injection wells to be determined is two (2). Including the time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 5.

Table 5.55: Case-3b: SP Flooding without Well Placement Optimization

Production Wells	10
Injection Wells	8
Reservoir Life (days)	73000
Number of Variables	5
Number of Generations	75
Population Size	8
Function Evaluation	600
Number of Realizations	3

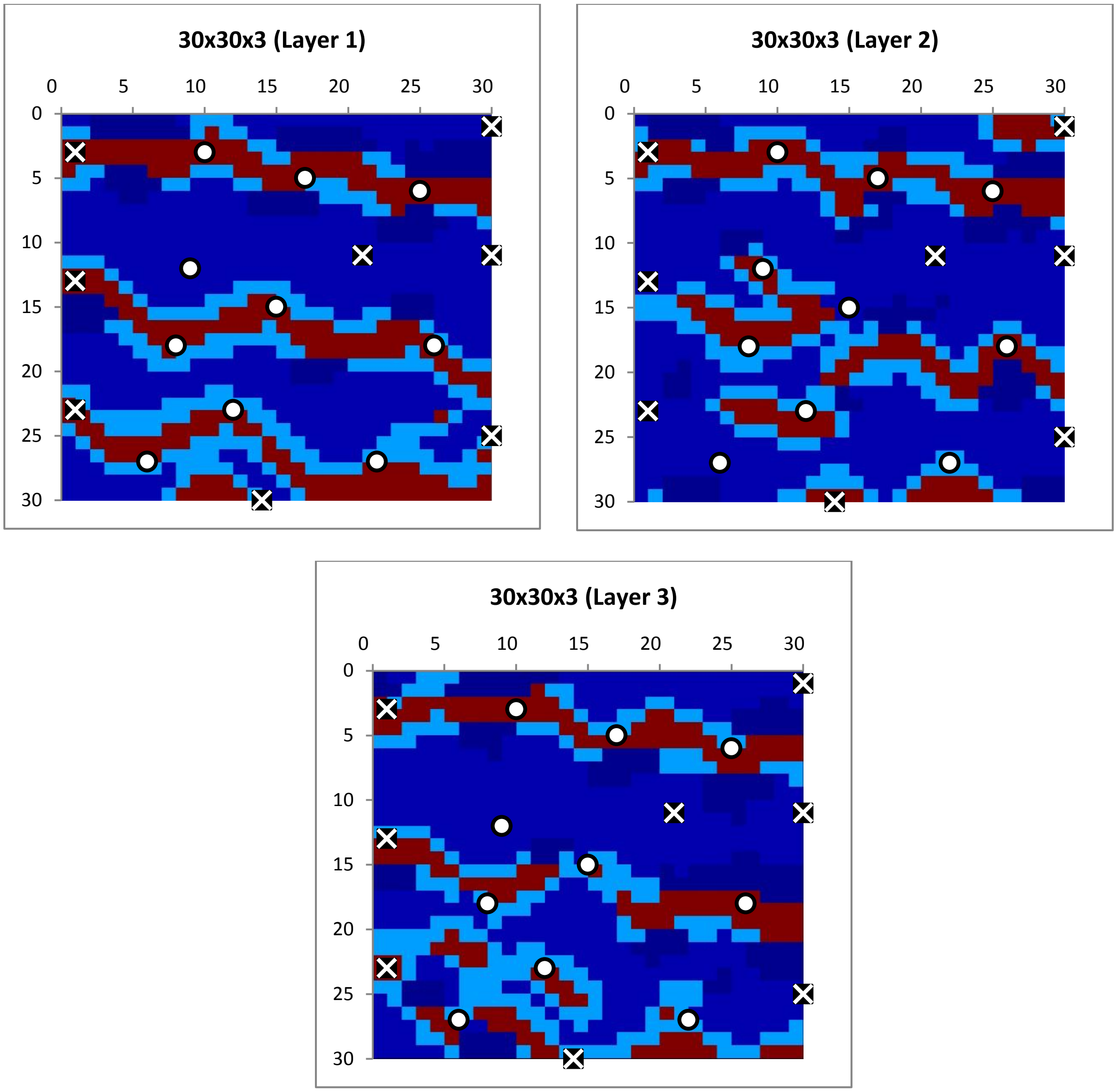


Figure 5.61: Solution of CMAES, DE and IWO for Case-3b

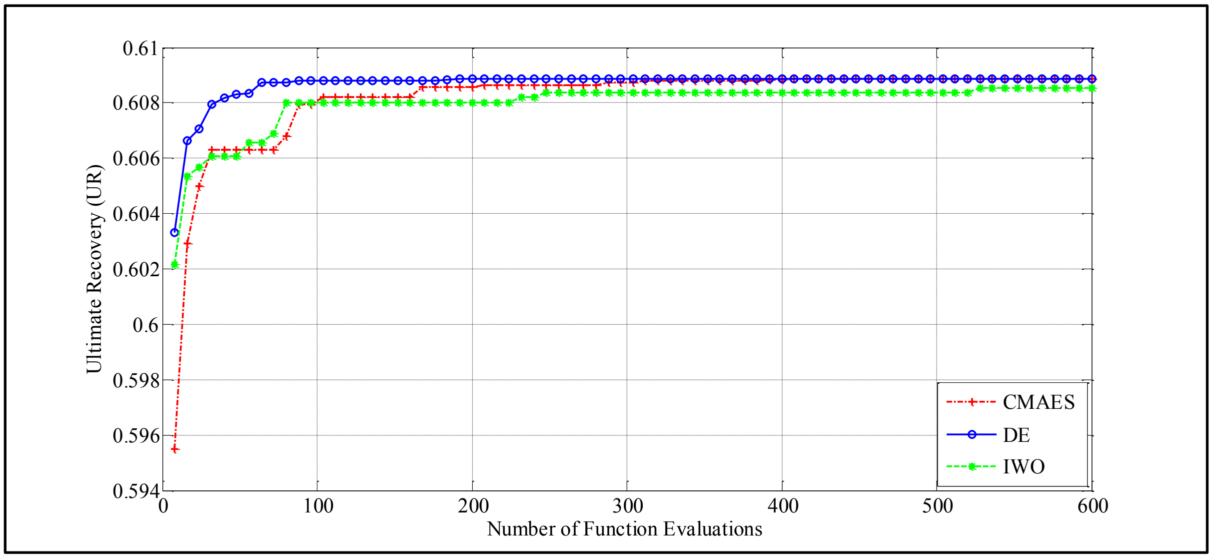


Figure 5.62: Comparison of Best Solution of CMAES, DE and IWO for Case-3b

Table 5.56: Best Solution of CMAES for Case-3b

<table>
<tr><th rowspan="2">No.</th><th colspan="2" rowspan="2">Production Wells</th><th colspan="2" rowspan="2">Injection Wells</th><th colspan="5">Optimized Variables</th><th rowspan="2">UR</th></tr>
<tr><th>Duration for Water Flooding</th><th>Duration for Surfactant Flooding</th><th>Duration for Polymer Flooding</th><th>Surfactant Conc.</th><th>Polymer Conc.</th></tr>
<tr><td></td><td>x</td><td>y</td><td>x</td><td>y</td><td>days</td><td>days</td><td>days</td><td>lb/STB</td><td>lb/STB</td><td></td></tr>
<tr><td>1</td><td>15</td><td>15</td><td>30</td><td>11</td><td rowspan="10">3429</td><td rowspan="10">1095</td><td rowspan="10">1825</td><td rowspan="10">0.99703</td><td rowspan="10">0.4977</td><td rowspan="10">0.6088</td></tr>
<tr><td>2</td><td>8</td><td>18</td><td>1</td><td>23</td></tr>
<tr><td>3</td><td>6</td><td>27</td><td>1</td><td>13</td></tr>
<tr><td>4</td><td>22</td><td>27</td><td>30</td><td>1</td></tr>
<tr><td>5</td><td>17</td><td>5</td><td>1</td><td>3</td></tr>
<tr><td>6</td><td>10</td><td>3</td><td>30</td><td>25</td></tr>
<tr><td>7</td><td>25</td><td>6</td><td>14</td><td>30</td></tr>
<tr><td>8</td><td>12</td><td>23</td><td>21</td><td>11</td></tr>
<tr><td>9</td><td>26</td><td>18</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>10</td><td>9</td><td>12</td></tr>
</table>

Table 5.57: Best Solution of DE for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	3434	1094	1821	1	0.4989	**0.6089**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Table 5.58: Best Solution of IWO for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	3267	1095	1825	0.9865	0.4849	**0.6085**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

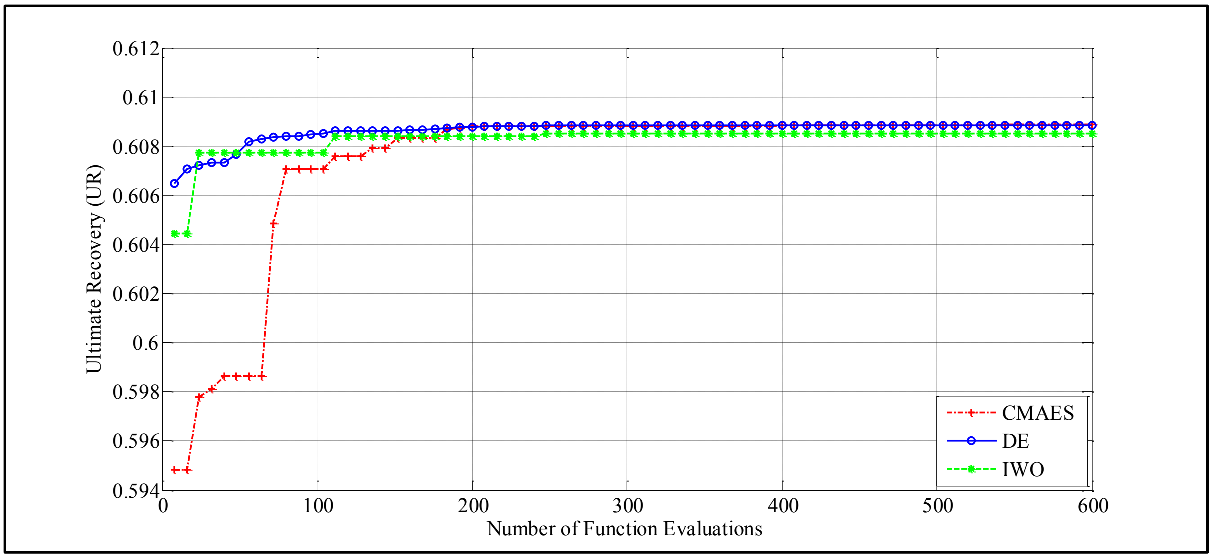


Figure 5.63: Comparison of Median Solution of CMAES, DE and IWO for Case-3b

Table 5.59: Median Solution of CMAES for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	3426	1095	1825	1	0.4914	**0.60886**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Table 5.60: Median Solution of DE for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	4703	1094	1825	0.9985	0.8189	**0.60884**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Table 5.61: Median Solution of IWO for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	3361	1095	1825	1	0.5233	**0.6085**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

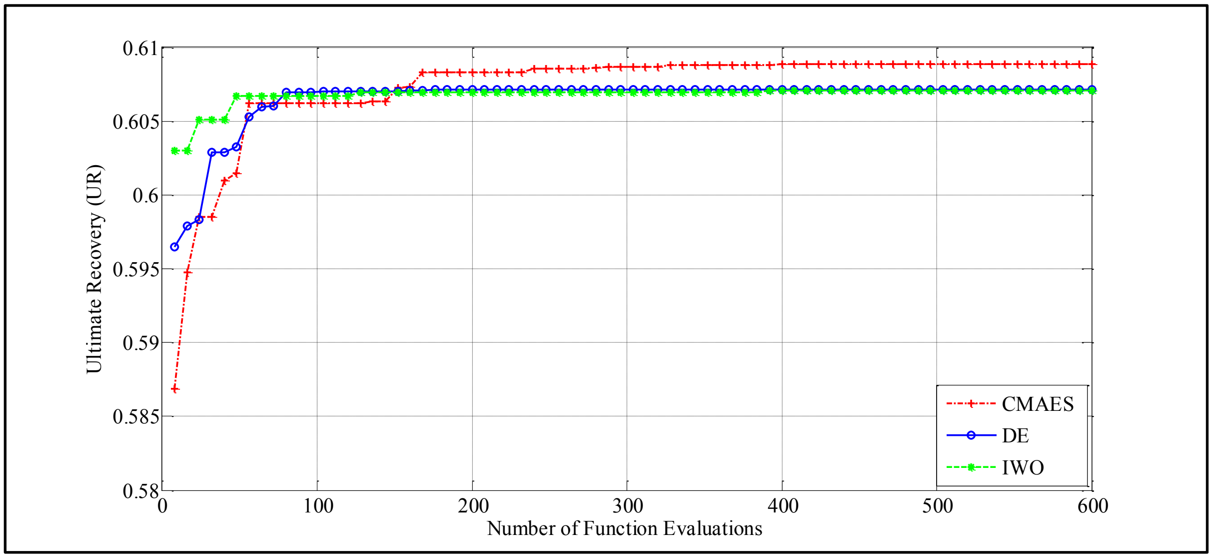


Figure 5.64: Comparison of Worst Solution of CMAES, DE and IWO for Case-3b

Table 5.62: Worst Solution of CMAES for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	y	x	y	days	days	days	lb/STB	lb/STB	
1	15	15	30	11	3334	1095	1825	1	0.4814	**0.60885**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Table 5.63: Worst Solution of DE for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	5320	218	1825	0.1590	0.9909	**0.60714**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Table 5.64: Worst Solution of IWO for Case-3b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	15	15	30	11	4640	886	1825	0.01	1	**0.60707**
2	8	18	1	23						
3	6	27	1	13						
4	22	27	30	1						
5	17	5	1	3						
6	10	3	30	25						
7	25	6	14	30						
8	12	23	21	11						
9	26	18								
10	9	12								

Discussion

This is a summary of the results presented

UR

The three stochastic algorithms showed almost the same values of UR with slight change in best, median and worst realizations.

Convergence

The three stochastic algorithms showed almost the same pattern for convergence using small steps and consuming less number of function evaluations.

Consistency

The three algorithms remained almost consistent for this case.

EOR process Selection

The three techniques showed invariable EOR process selection for best, median and worst realizations. The selected EOR process configuration for this case is waterflooding followed by surfactant flooding and then polymer flooding.

5.5.2.1.3 Comparison of Case-3a, Case-3b and Waterflooding

A base case having fixed well locations with simple waterflooding was run and compared with SP flooding process with well placement optimization (Case-3a) and SP flooding process without well placement optimization (Case-3b). Well placement configuration for the base case and Case-3b remains the same. Table 5.65, Figs. 5.65 and 5.66 showed the summary of Case-3a, Case-3b and waterflooding for best, median and worst realizations for Reservoir Model-1. The incremental UR values are calculated by comparing each of Case-3a and Case-3b with waterflooding.

It is evident from the results that there is an increase in the ultimate recovery after the implementation of stochastic optimization techniques. An increase of around 3.61% to 3.93% is observed when SP flooding is optimized without well placement optimization. However, SP flooding with well placement optimization showed increase in ultimate recovery in the range of about 4.37% to 8.94%.

Table 5.65: Comparison of Case3a, Case-3b and Waterflooding

Reservoir Model	Stochastic Technique	Solution Type	SP Flooding with WPO (Case-3a)	SP Flooding without WPO (Case-3b)	Water flooding	Incremental UR(Case-3a)	Incremental UR(Case-3b)
						%	%
Reservoir Model-1	CMAES	Best	0.64	0.61	0.59	8.94	3.91
		Median	0.63	0.61	0.59	7.44	3.92
		Worst	0.62	0.61	0.59	6.61	3.92
	DE	Best	0.63	0.61	0.59	8.35	3.93
		Median	0.63	0.61	0.59	8.07	3.92
		Worst	0.61	0.61	0.59	4.81	3.63
	IWO	Best	0.63	0.61	0.59	6.67	3.86
		Median	0.61	0.61	0.59	4.88	3.86
		Worst	0.61	0.61	0.59	4.37	3.61

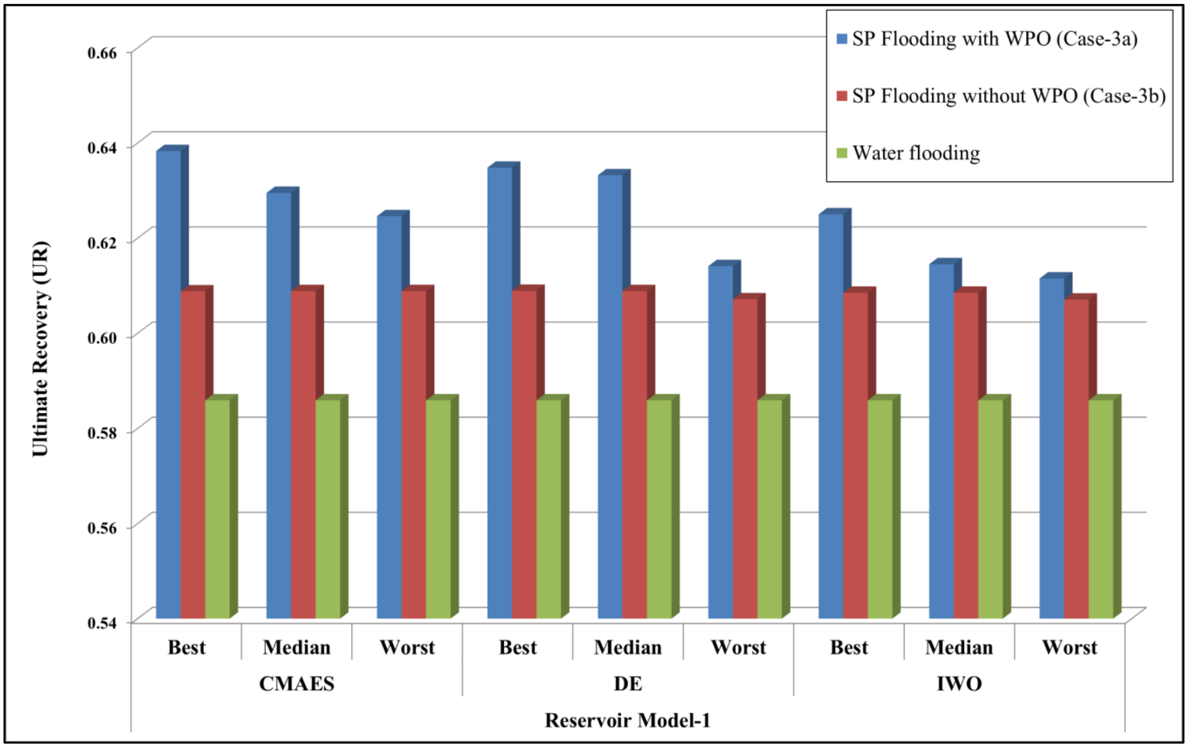


Figure 5.65: Comparison of Case3a, Case-3b and Waterflooding

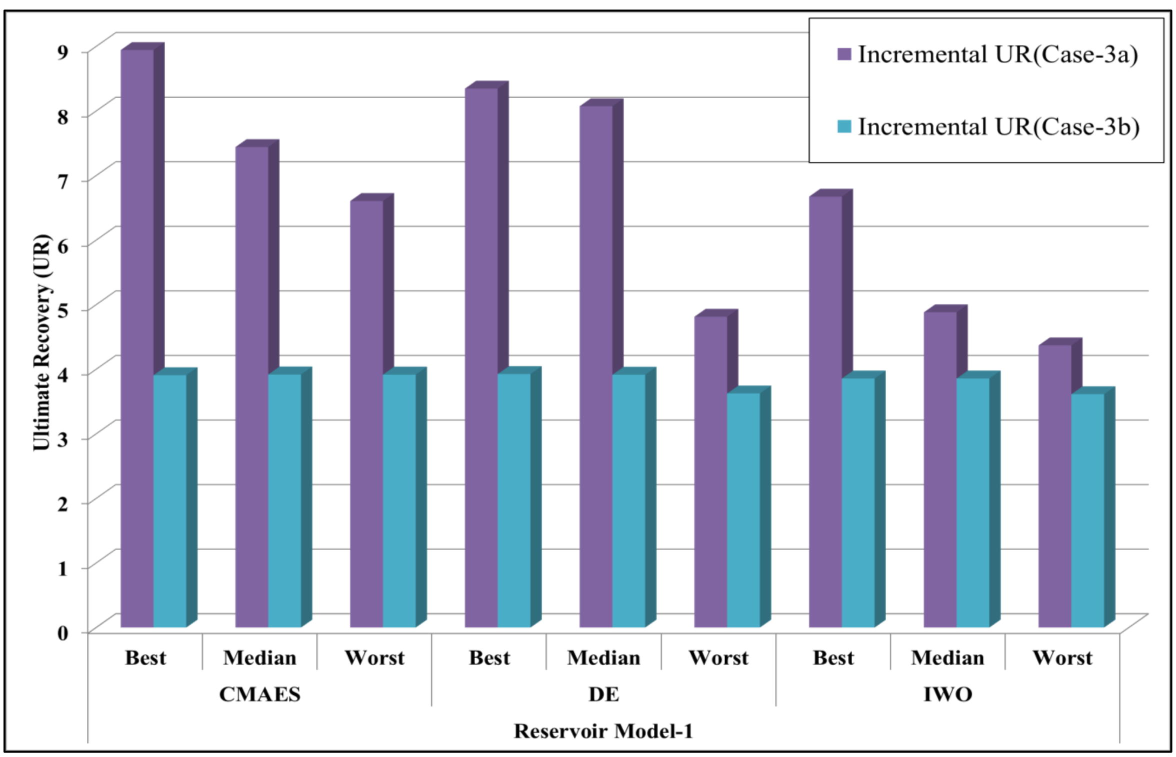


Figure 5.66: Incremental UR from Case-3a, Case-3b

5.5.2.2 Case-4: UR Optimization for Reservoir Model-2 (Fully Heterogeneous Reservoir)

Optimization study for Reservoir Model-2 is performed using three stochastic optimization algorithms namely Covariance Matrix Adaptation-Evolutionary strategy (CMAES), Differential Evolution (DE) and Invasive Weed Optimization (IWO).

1. Optimization of surfactant-polymer flooding with well placement optimization (See section 5.5.2.2.1).
2. Optimization of surfactant-polymer flooding without well placement optimization (See section 5.5.2.2.2).

In each of these subsections, three realizations of the three optimization algorithms (CMAES, DE and IWO) were generated and the Best, Median and Worst solutions were selected for analysis of performance. Furthermore, Section 5.5.2.2.3 compares the results of Sections 5.5.2.2.1 and 5.5.2.2.2.

5.5.2.2.1 Case-4a: SP Flooding with Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding with well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic optimization algorithms. Table 5.66 shows the input data for this case. Table 5.67 to Table 5.75, and Figs. 5.67 to 5.78 show the results obtained after optimization.

Table 5.66 shows that thirteen (13) producers and twelve (12) injectors were used for this case making a total of twenty-five (25) wells. The number of (*x*,*y*) well locations to be determined is fifty (50) while the surfactant and polymer concentrations in injection wells to be determined is two (2). Including time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters 55.

Table 5.66: Case-4a: SP Flooding with Well Placement Optimization

Production Wells	13
Injection Wells	12
Reservoir Life (days)	73000
Number of Variables	55
Number of Generations	190
Population Size	16
Function Evaluation	3040
Number of Realizations	3

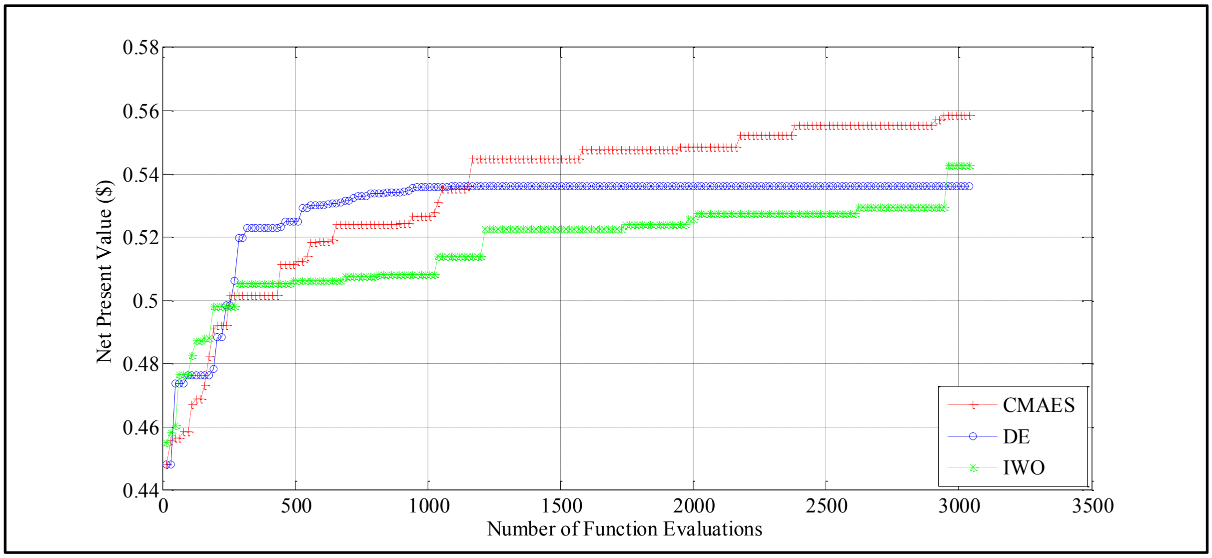


Figure 5.67: Comparison of Best Solution of CMAES, DE and IWO for Case-4a

Table 5.67: Best Solution of CMAES for Case-4a

Optimized Variables										**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	12	17	49	50	2190	1095	1825	1.00	0.48	**0.5585**
2	3	44	47	46						
3	4	4	50	27						
4	12	22	50	5						
5	1	10	42	40						
6	15	9	37	44						
7	1	17	50	50						
8	6	50	40	50						
9	30	26	50	16						
10	1	44	38	40						
11	16	18	30	1						
12	1	6	50	11						
13	9	18								

Table 5.68: Best Solution of DE for Case-4a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	9	40	38	36	2190	54	1825	0.02	0.46	**0.5362**
2	5	47	44	8						
3	23	40	5	4						
4	2	47	9	9						
5	46	10	16	12						
6	45	1	1	4						
7	24	31	32	37						
8	49	5	34	50						
9	20	46	2	13						
10	40	5	4	15						
11	36	27	24	21						
12	50	38	15	47						
13	50	2								

Table 5.69: Best Solution of IWO for Case-4a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	50	10	35	45	2190	1095	1730	0.8954	0.6162	**0.5427**
2	24	16	25	47						
3	50	26	11	36						
4	50	38	6	40						
5	20	21	9	15						
6	30	1	22	44						
7	44	3	1	50						
8	47	6	42	30						
9	38	16	24	37						
10	28	11	25	49						
11	14	1	10	49						
12	29	1	26	34						
13	46	7								

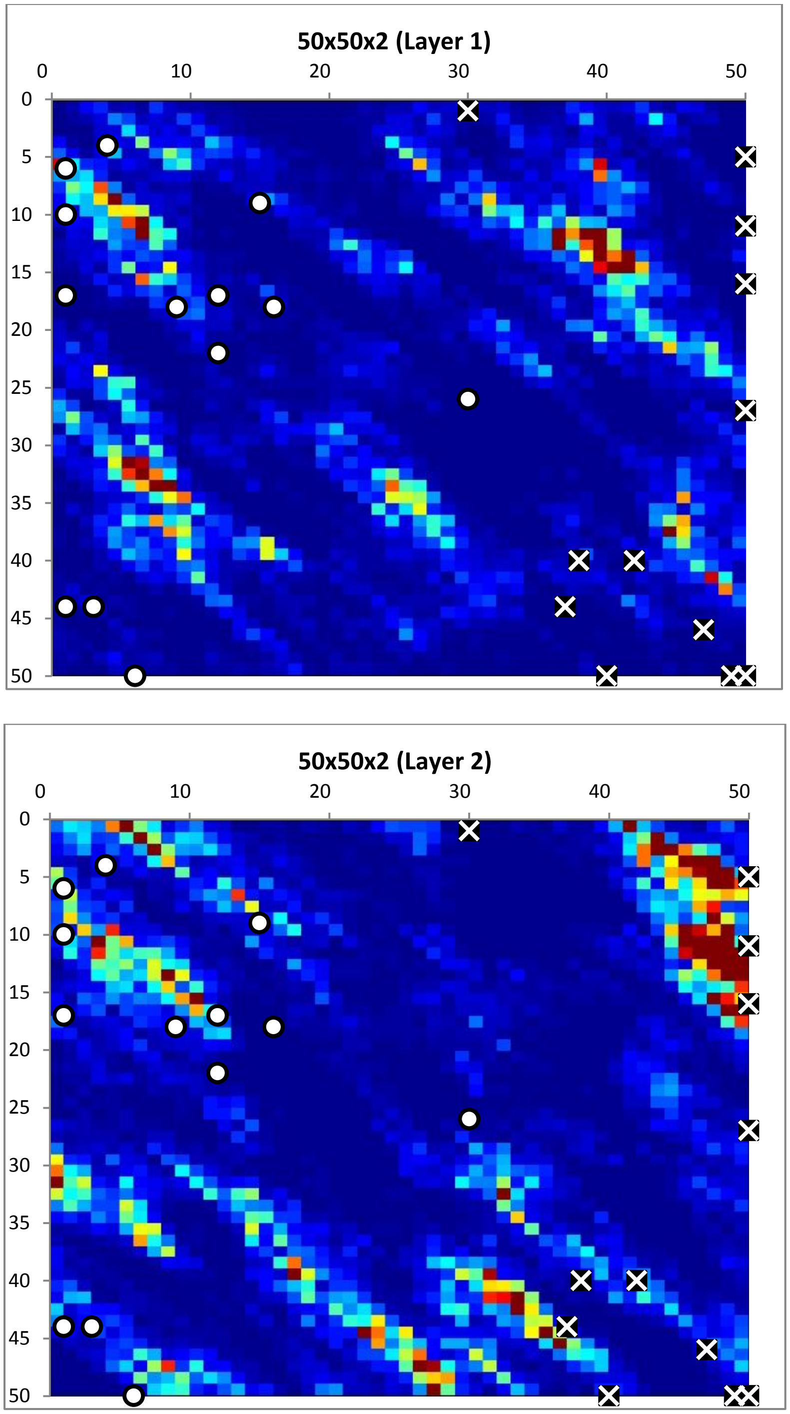
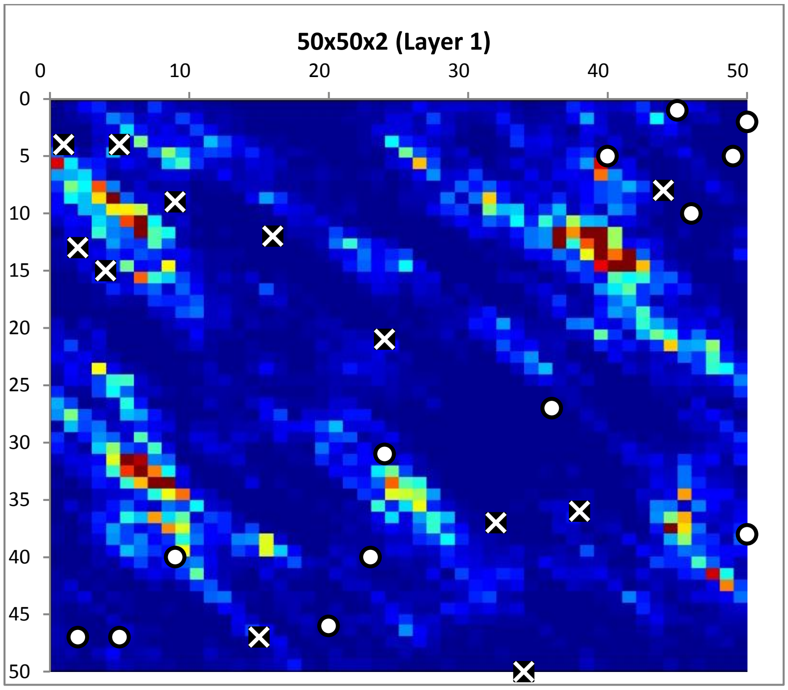


Figure 5.68: Best Solution of CMAES for Case-4a



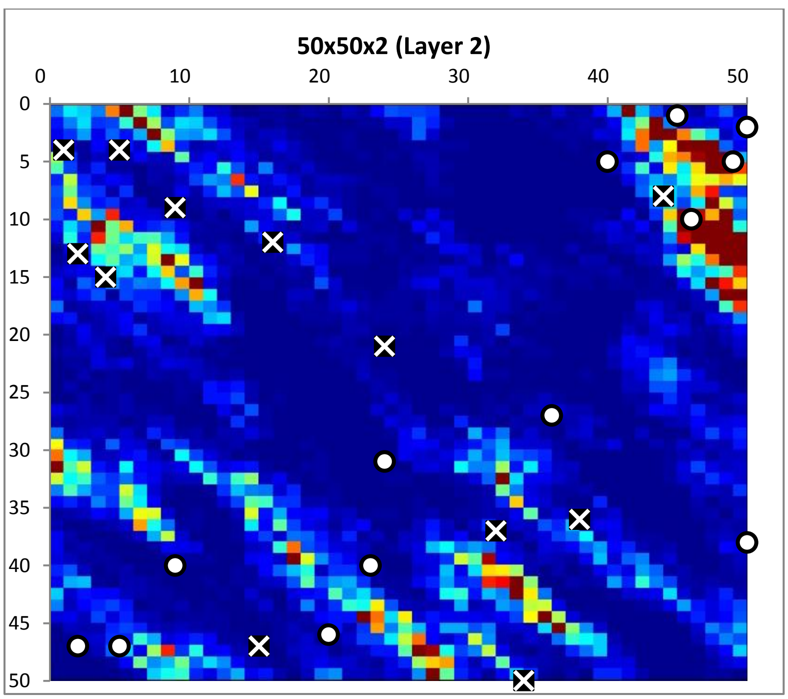


Figure 5.69: Best Solution of DE for Case-4a

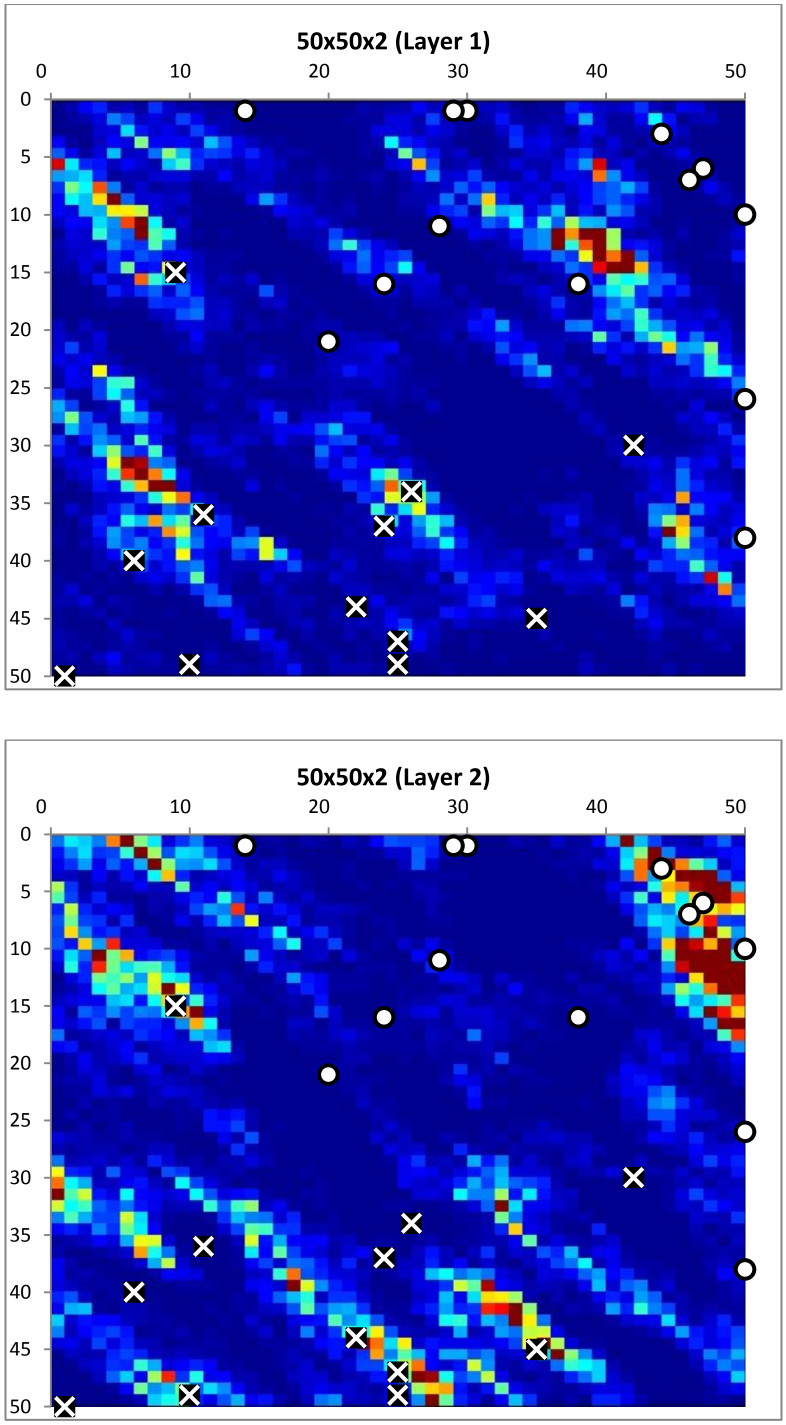


Figure 5.70: Best Solution of IWO for Case-4a

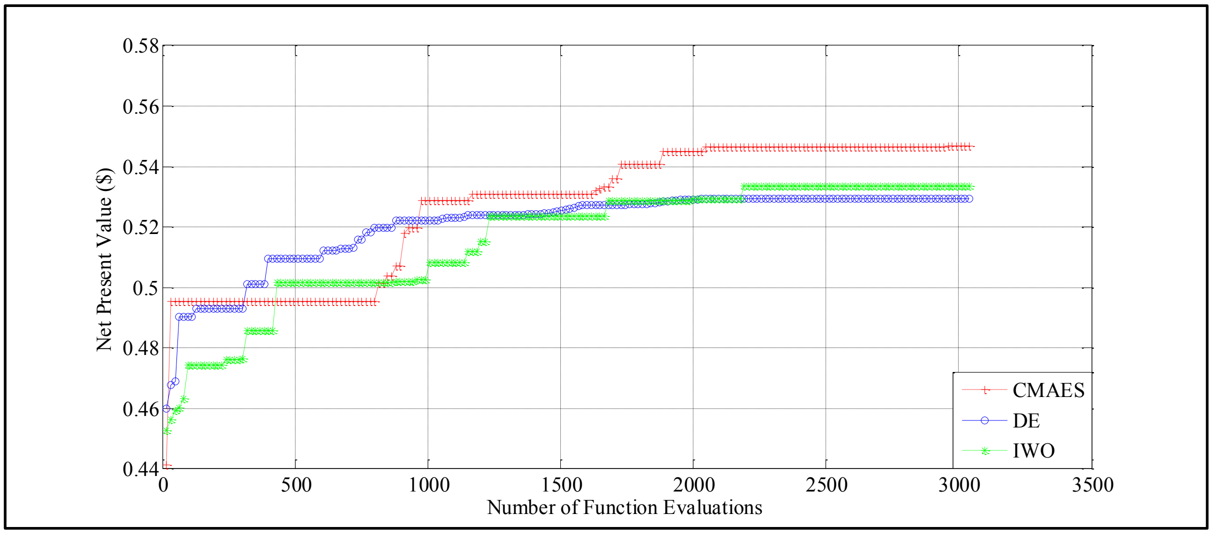


Figure 5.71: Comparison of Median Solution of CMAES, DE and IWO for Case-4a

Table 5.70: Median Solution of CMAES for Case-4a

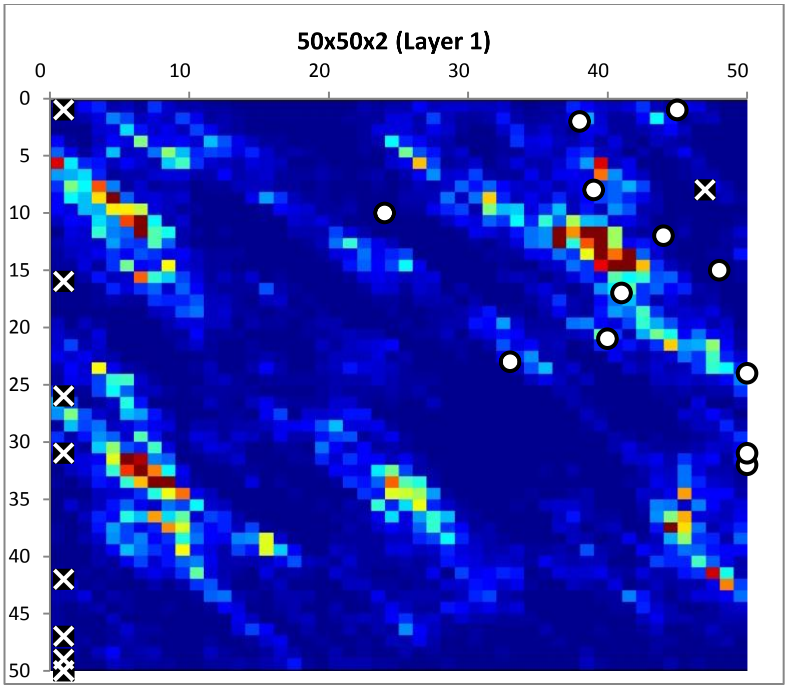
Optimized Variables											**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.		
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**		
1	44	12	1	50							
2	50	24	1	31							
3	41	17	1	50							
4	48	15	1	47							
5	45	1	1	50							
6	38	2	1	16							
7	45	1	47	8	7665	1095	1739	0.8277	0.2466		**0.5468**
8	39	8	1	1							
9	40	21	1	49							
10	24	10	1	42							
11	50	32	1	50							
12	50	31	1	26							
13	33	23									

Table 5.71: Median Solution of DE for Case-4a

Optimized Variables										**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	1	9	12	32						
2	20	41	43	16						
3	25	18	9	20						
4	29	28	37	39						
5	17	4	35	36						
6	29	4	45	14						
7	13	50	35	50	6041	953	1825	0.9996	0.4145	**0.5294**
8	3	26	14	41						
9	50	43	12	6						
10	43	33	22	21						
11	2	42	37	10						
12	1	12	21	23						
13	24	1								

Table 5.72: Median Solution of IWO for Case-4a

Optimized Variables										**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	19	1	16	10						
2	1	40	48	39						
3	1	39	49	3						
4	4	45	44	36						
5	10	50	26	1						
6	10	30	47	45						
7	5	32	47	16	2190	1095	1825	1.00	0.2316	**0.5337**
8	9	46	50	3						
9	20	48	44	28						
10	1	23	47	36						
11	3	30	27	1						
12	2	25	48	19						
13	3	45								



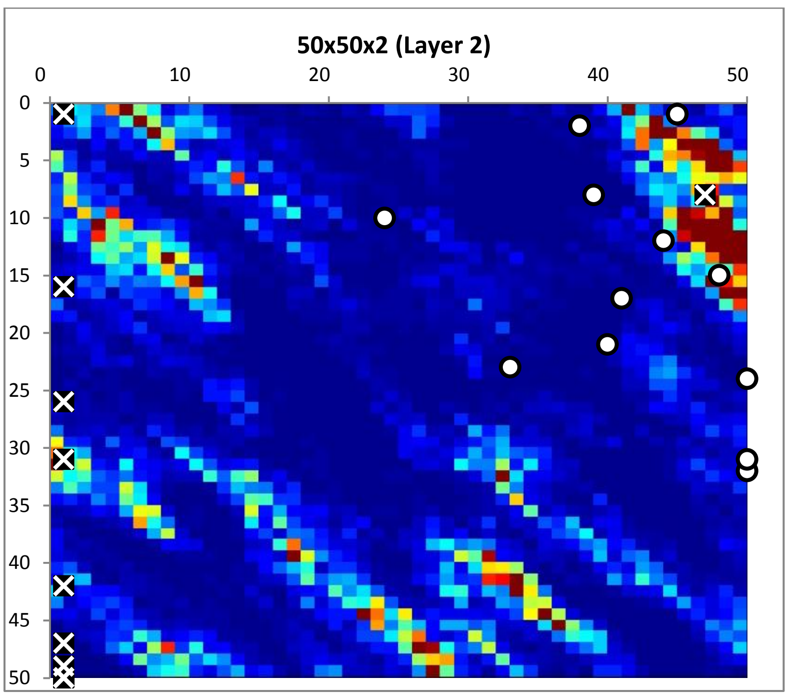


Figure 5.72: Median Solution of CMAES for Case-4a

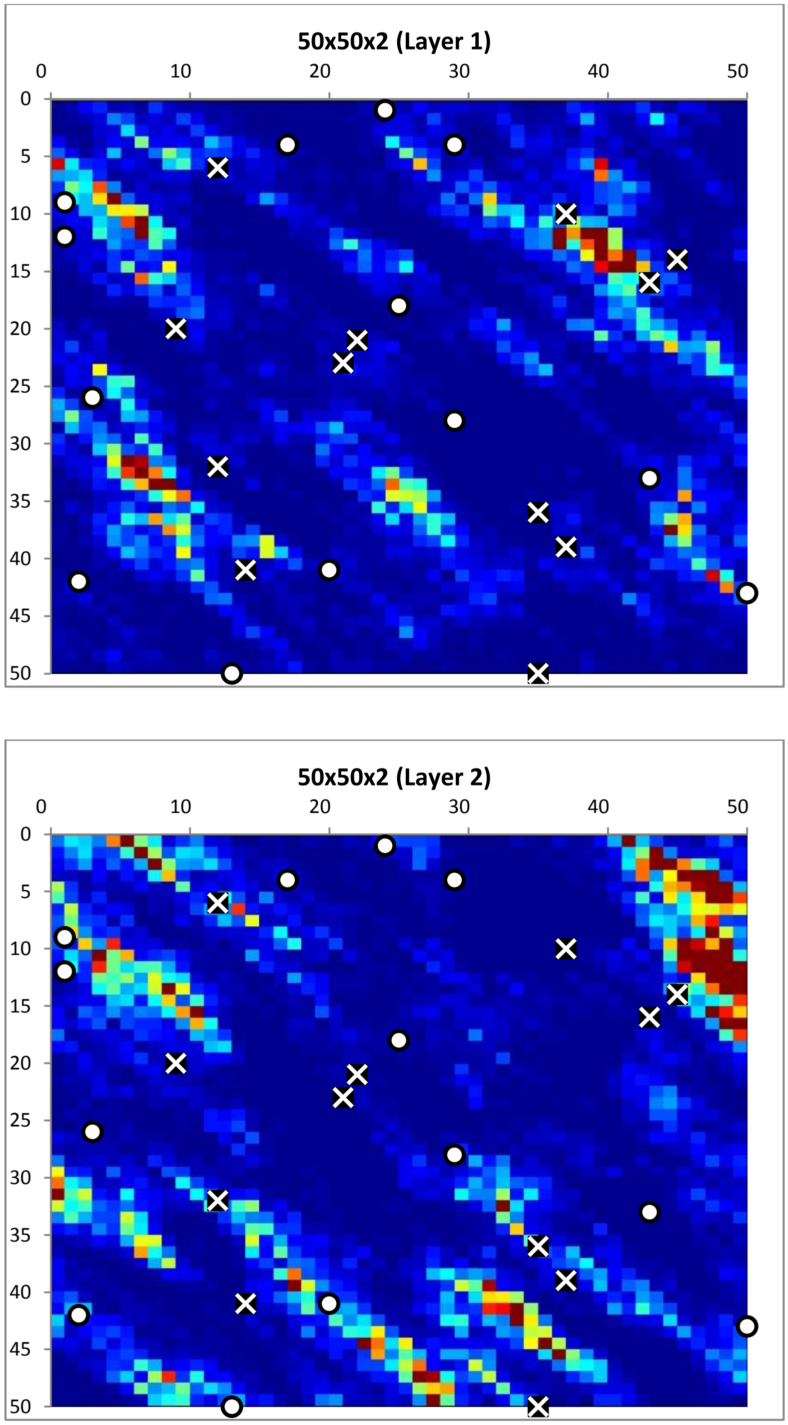


Figure 5.73: Median Solution of DE for Case-4a

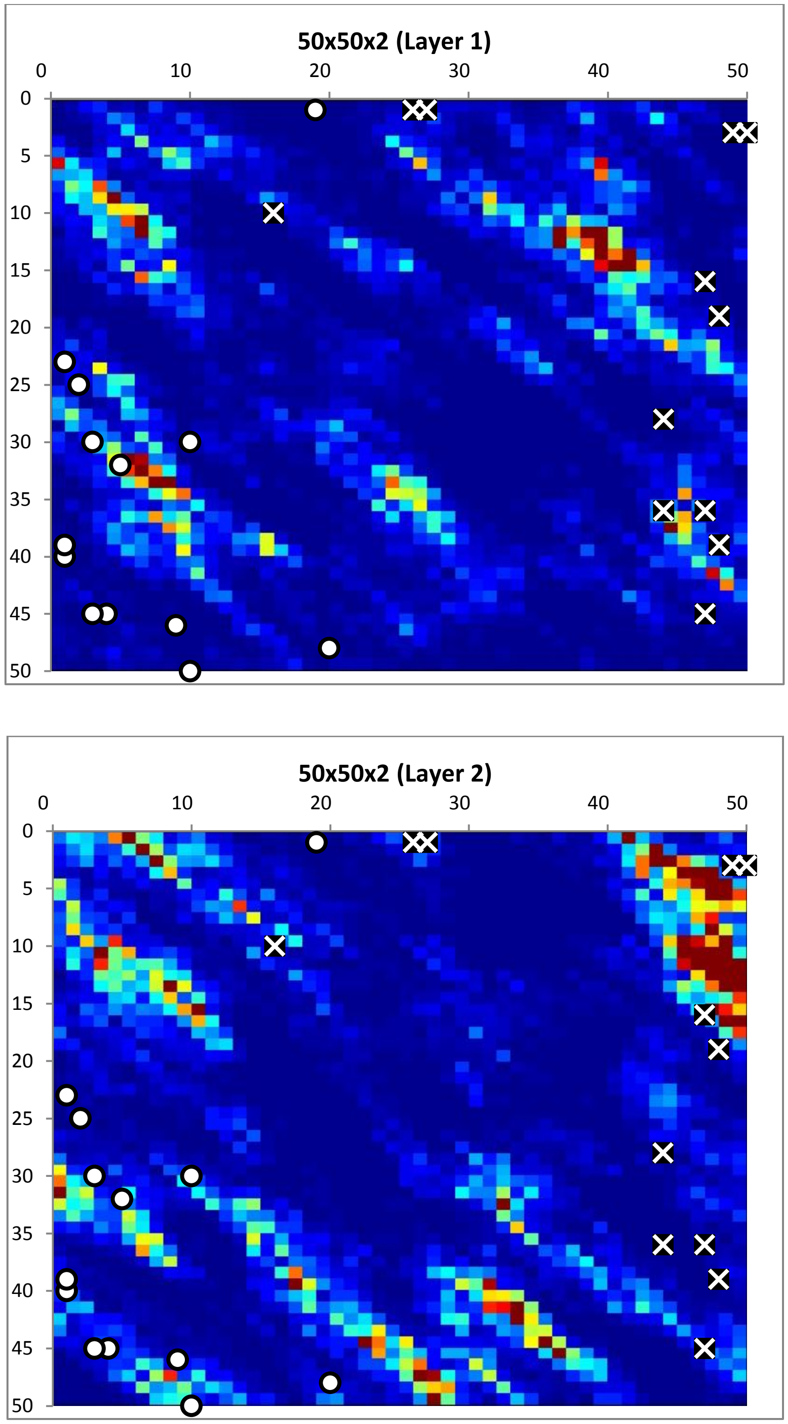


Figure 5.74: Median Solution of IWO for Case-4a

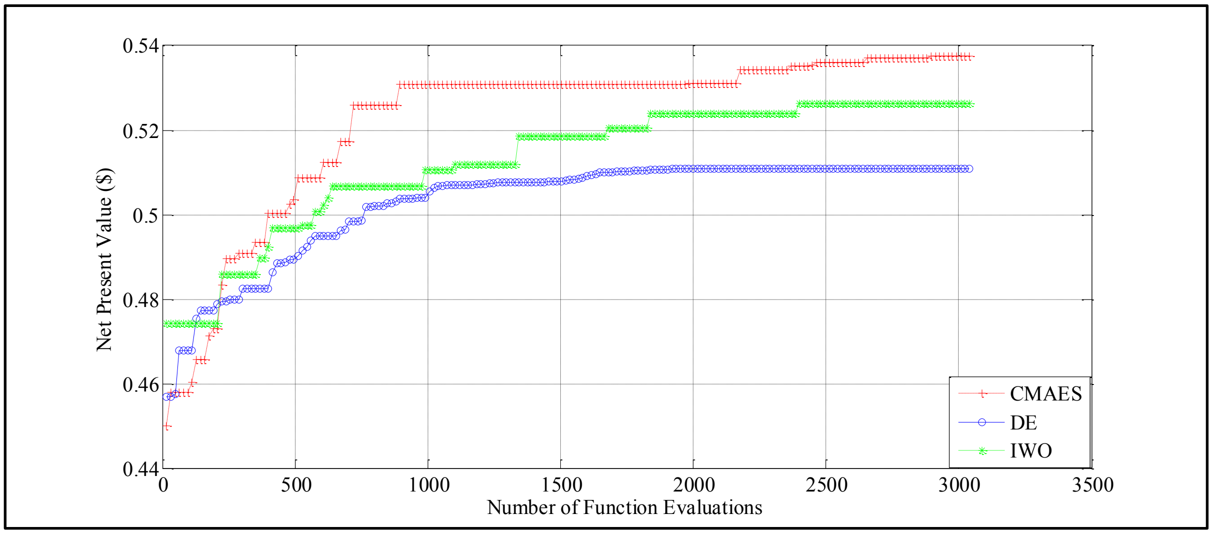


Figure 5.75: Comparison of Worst Solution of CMAES, DE and IWO for Case-4a

Table 5.73: Worst Solution of CMAES for Case-4a

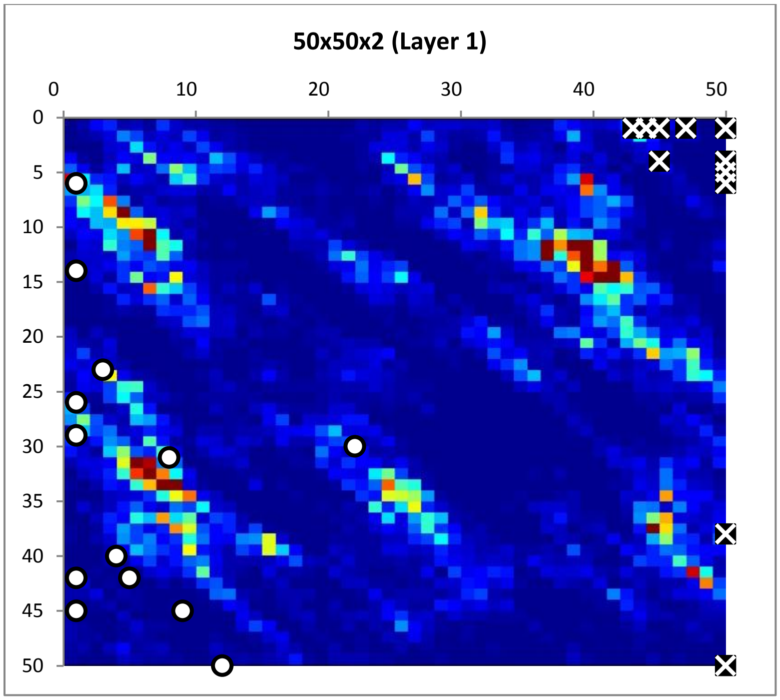
Optimized Variables										**UR**
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	5	42	45	1	7073	1095	1196	0.8130	0.2103	**0.5375**
2	1	45	50	38						
3	1	42	50	50						
4	8	31	44	1						
5	3	23	50	1						
6	1	29	50	4						
7	1	6	50	6						
8	1	26	47	1						
9	9	45	50	5						
10	22	30	45	4						
11	4	40	43	1						
12	12	50	50	1						
13	1	14								

Table 5.74: Worst Solution of DE for Case-4a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	37	41	1	50	4594	824	1824	1.00	0.2436	**0.5109**
2	49	49	37	30						
3	16	41	20	43						
4	36	1	42	25						
5	25	16	1	47						
6	47	2	12	1						
7	23	26	41	45						
8	16	41	41	24						
9	31	50	1	14						
10	20	50	1	50						
11	22	1	33	30						
12	28	43	3	18						
13	26	9								

Table 5.75: Worst Solution of IWO for Case-4a

Optimized Variables										UR
No.	Production Wells		Injection Wells		Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	33	22	1	50	7455	715	1206	0.8814	0.2890	**0.5263**
2	46	24	29	10						
3	41	28	20	1						
4	50	11	4	49						
5	40	18	1	28						
6	50	24	1	43						
7	19	18	15	28						
8	49	18	3	50						
9	48	29	3	50						
10	26	13	17	50						
11	33	13	31	1						
12	28	16	39	50						
13	45	11								



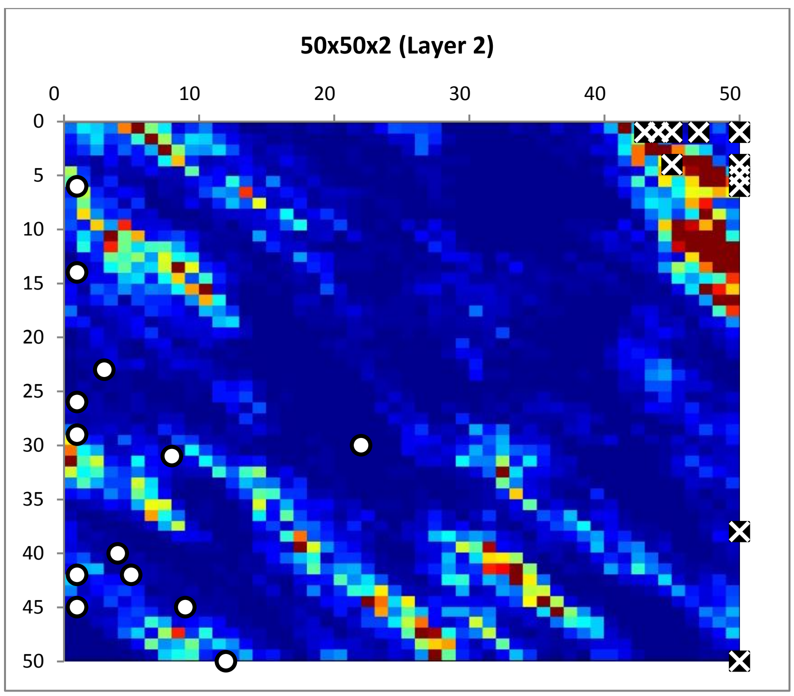
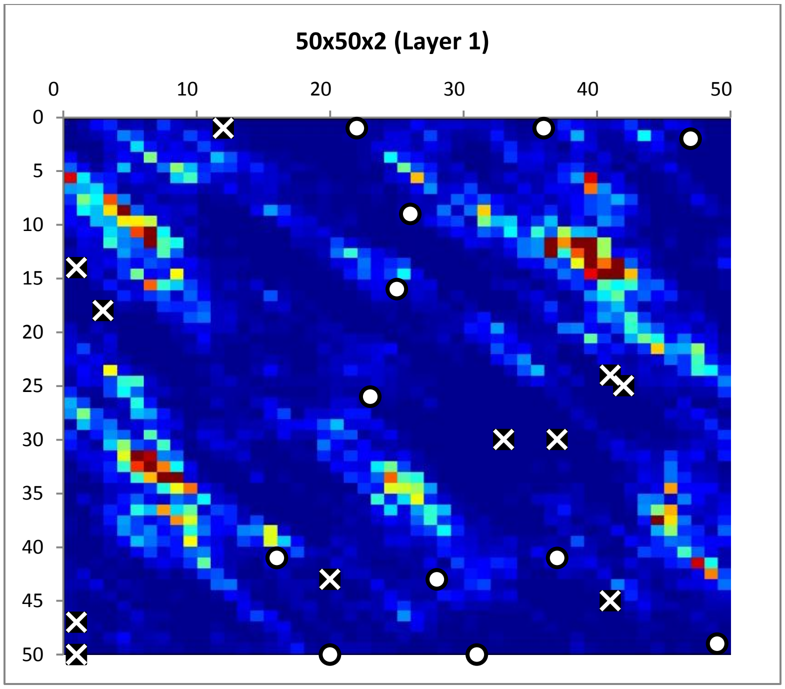


Figure 5.76: Worst Solution of CMAES for Case-4a



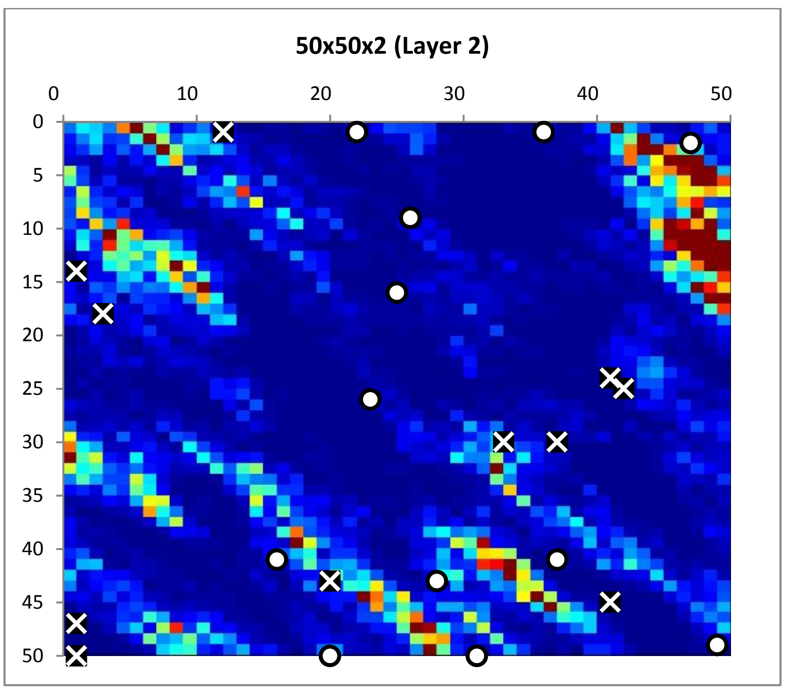
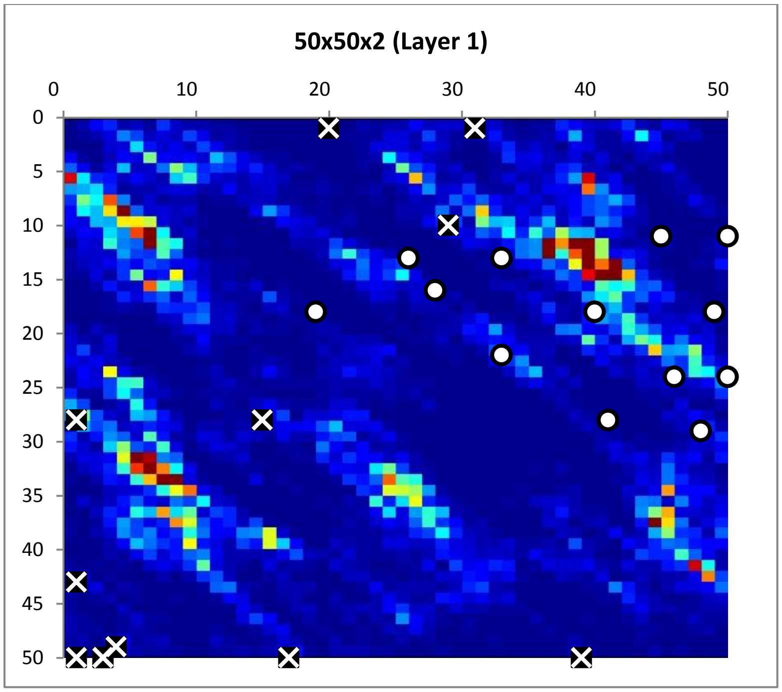


Figure 5.77: Worst Solution of DE for Case-4a



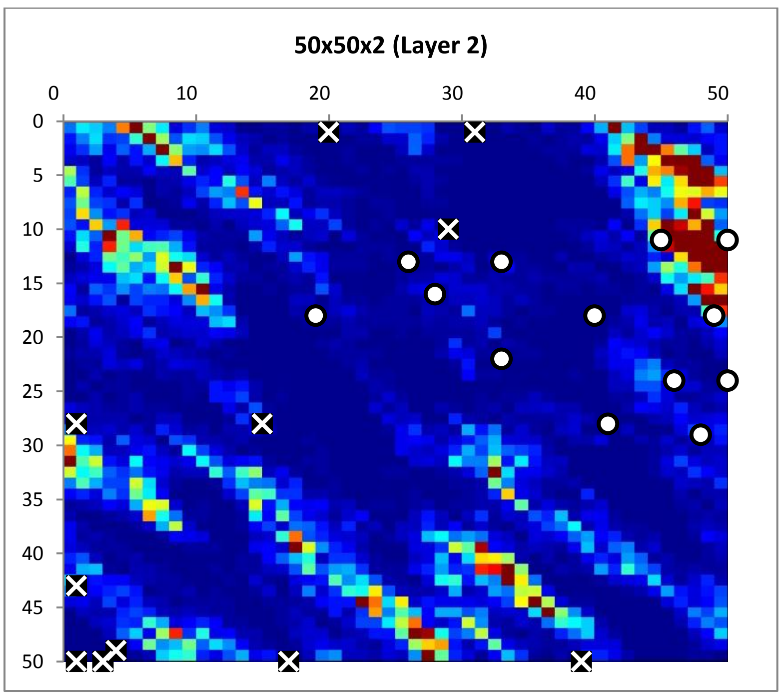


Figure 5.78: Worst Solution of IWO for Case-4a

Discussion

This is a summary of the results presented

UR

CMAES showed highest values of UR amongst the three stochastic algorithms for best, median and worst realizations. IWO stands second best algorithm for the determination of maximum UR values which is followed by DE.

Convergence

CMAES and IWO showed continuous improvement with small steps towards the optimized solution. However, CMAES showed higher tendency of convergence towards a better optimized solution than DE and IWO. DE showed early convergence in all three realizations.

Consistency

The three techniques remained almost consistent for this case.

EOR process Selection

The three techniques showed invariable EOR process selection for best, median and worst realizations. The selected EOR process configuration for this case is waterflooding followed by surfactant flooding and then polymer flooding.

Well Placement

Well placement in this optimization problem is significantly influenced by the heterogeneity of the reservoir. The well placement pattern for CMAES showed that the best results can be achieved if the injection configuration follows the peripheral injection scheme. Furthermore, DE follows the permeability distribution profile for the wells while IWO placed majority of the wells in high permeability zones.

In case of clustering of wells in one location, check the minimum well spacing that guarantees the safety of each well. If it is met than that configuration is valid, otherwise not. Moreover, the placement of the injectors and producers was significantly influenced by the permeability distribution pattern in the reservoir.

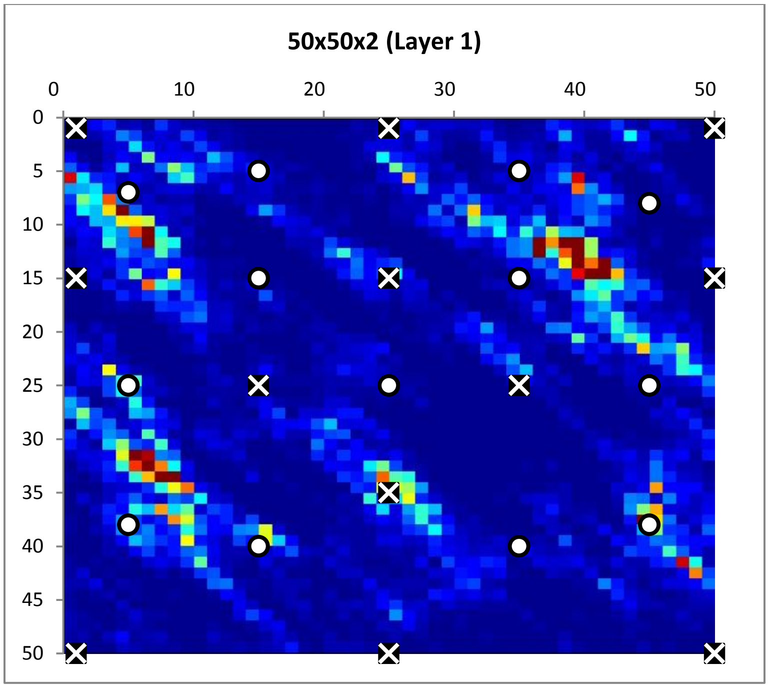
5.5.2.2.2 Case-4b: SP Flooding without Well Placement Optimization

In this section, results of the optimization study carried out for SP flooding without well placement are presented for CMAES, DE and IWO. We ran each optimization algorithm on this problem three times so that three realizations of the solutions are obtained from each algorithm. The best, median and worst solutions are presented for the comparison between the stochastic optimization algorithms. Table 5.76 shows the input data for this case. Table 5.77 to Table 5.85, and Figs. 5.79 to 5.82 show the results obtained after optimization.

Table 5.76 shows that thirteen (13) producers and twelve (12) injectors were used for this case and their locations are fixed as shown in Fig. 5.79. The surfactant and polymer concentrations in injection wells to be determined is two (2). Including the time for sequential flooding (Water Flooding, Surfactant Flooding and Polymer Flooding) makes the total number of optimization parameters equal to 5.

Table 5.76: Case-4b: SP Flooding without Well Placement

Production Wells	13
Injection Wells	12
Reservoir Life (days)	73000
Number of Variables	5
Number of Generations	75
Population Size	8
Function Evaluation	600
Number of Realizations	3



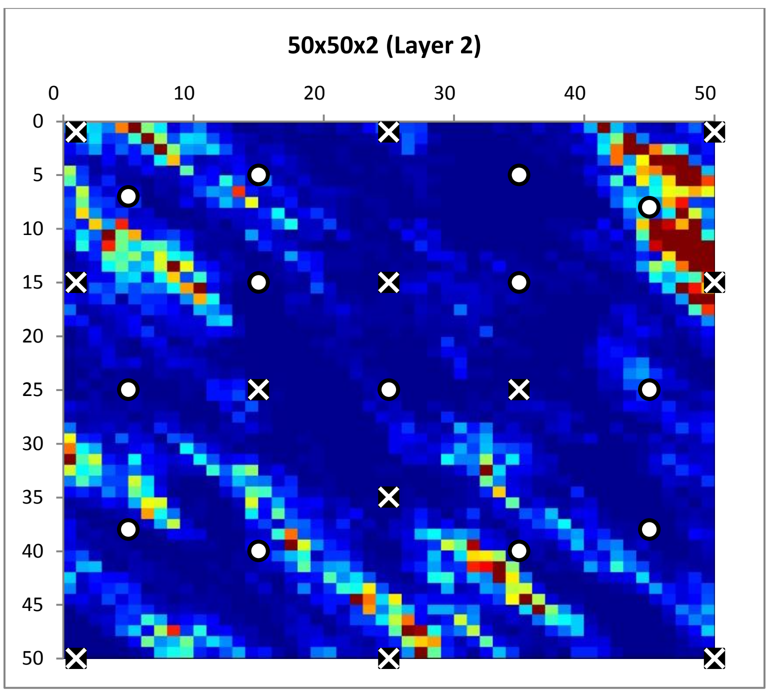


Figure 5.79: Solution of CMAES, DE and IWO for Case-4b

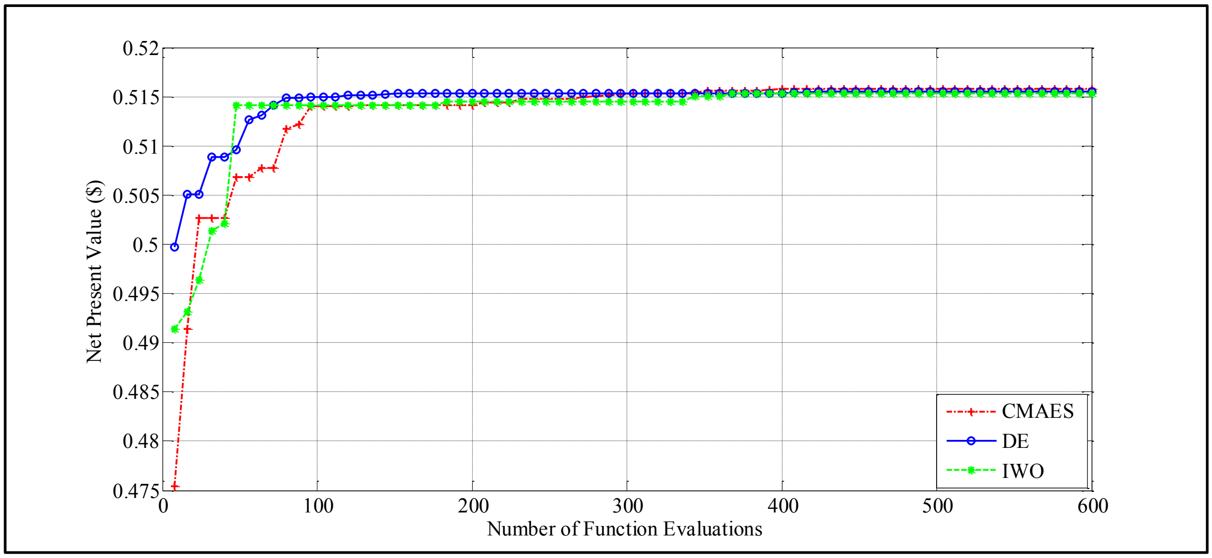


Figure 5.80: Comparison of Best Solution of CMAES, DE and IWO for Case-4b

Table 5.77: Best Solution of CMAES for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	3330	1095	1825	1.00	0.5145	**0.5158**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.78: Best Solution of DE for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	2981	1095	1824	0.9995	0.5247	**0.5155**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.79: Best Solution of IWO for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	3690	1095	1825	1.00	0.4688	**0.5154**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

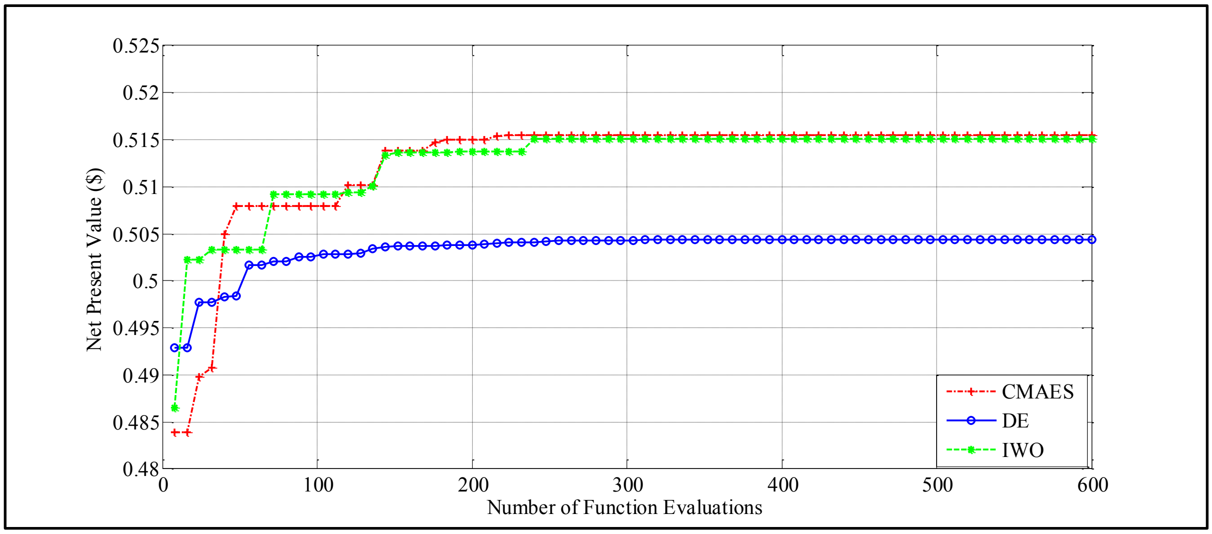


Figure 5.81: Comparison of Median Solution of CMAES, DE and IWO for Case-4b

Table 5.80: Median Solution of CMAES for Case-4b

<table>
<tr><th rowspan="2">No.</th><th colspan="2" rowspan="2">Production Wells</th><th colspan="2" rowspan="2">Injection Wells</th><th colspan="5">Optimized Variables</th><th rowspan="2">UR</th></tr>
<tr><th>Duration for Water Flooding</th><th>Duration for Surfactant Flooding</th><th>Duration for Polymer Flooding</th><th>Surfactant Conc.</th><th>Polymer Conc.</th></tr>
<tr><td></td><td>x</td><td>y</td><td>x</td><td>y</td><td>days</td><td>days</td><td>days</td><td>lb/STB</td><td>lb/STB</td><td></td></tr>
<tr><td>1</td><td>25</td><td>25</td><td>25</td><td>15</td><td rowspan="13">2979</td><td rowspan="13">1095</td><td rowspan="13">1825</td><td rowspan="13">1.00</td><td rowspan="13">0.5248</td><td rowspan="13">0.5155</td></tr>
<tr><td>2</td><td>15</td><td>15</td><td>25</td><td>35</td></tr>
<tr><td>3</td><td>35</td><td>15</td><td>15</td><td>25</td></tr>
<tr><td>4</td><td>15</td><td>40</td><td>35</td><td>25</td></tr>
<tr><td>5</td><td>35</td><td>40</td><td>1</td><td>1</td></tr>
<tr><td>6</td><td>45</td><td>8</td><td>1</td><td>15</td></tr>
<tr><td>7</td><td>5</td><td>7</td><td>50</td><td>50</td></tr>
<tr><td>8</td><td>5</td><td>25</td><td>50</td><td>1</td></tr>
<tr><td>9</td><td>5</td><td>38</td><td>50</td><td>15</td></tr>
<tr><td>10</td><td>45</td><td>25</td><td>1</td><td>50</td></tr>
<tr><td>11</td><td>45</td><td>38</td><td>25</td><td>1</td></tr>
<tr><td>12</td><td>15</td><td>5</td><td>25</td><td>50</td></tr>
<tr><td>13</td><td>35</td><td>5</td><td colspan="2"></td></tr>
</table>

Table 5.81: Median Solution of DE for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	6414	1095	1824	0.9998	0.4589	**0.5043**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.82: Median Solution of IWO for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	2944	1088	1825	1.00	0.5302	**0.5151**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

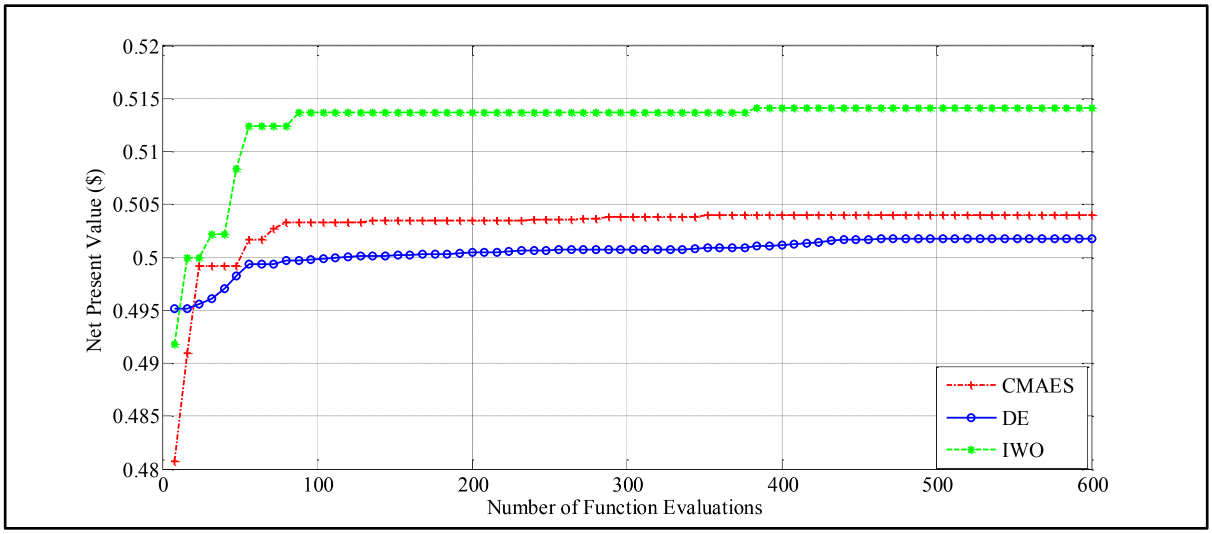


Figure 5.82: Comparison of Worst Solution of CMAES, DE and IWO for Case-4b

Table 5.83: Worst Solution of CMAES for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables					UR
					Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	2969	1095	106	1.00	0.8119	**0.5039**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.84: Worst Solution of DE for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	6237	756	1825	1.00	0.4359	**0.5017**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Table 5.85: Worst Solution of IWO for Case-4b

No.	Production Wells		Injection Wells		Optimized Variables: Duration for Water Flooding	Duration for Surfactant Flooding	Duration for Polymer Flooding	Surfactant Conc.	Polymer Conc.	**UR**
	x	**y**	**x**	**y**	**days**	**days**	**days**	**lb/STB**	**lb/STB**	
1	25	25	25	15	3552	1095	1703	0.9958	0.4588	**0.5141**
2	15	15	25	35						
3	35	15	15	25						
4	15	40	35	25						
5	35	40	1	1						
6	45	8	1	15						
7	5	7	50	50						
8	5	25	50	1						
9	5	38	50	15						
10	45	25	1	50						
11	45	38	25	1						
12	15	5	25	50						
13	35	5								

Discussion

This is a summary of the results presented

UR

For the best and median realization, CMAES and IWO showed same UR values. IWO performed better than the other two techniques in worst realization where it is followed by CMAES and DE. However, DE is unable to meet CMAES and IWO in median and worst realizations.

Convergence

The three algorithms under consideration showed good convergence towards the optimized solution.

Consistency

All algorithms showed consistent results in all realizations.

EOR process Selection

The three techniques showed invariable EOR process selection for best, median and worst realizations. The selected EOR process configuration for this case is waterflooding followed by surfactant flooding and then polymer flooding.

5.5.2.2.3 Comparison of Case-4a, Case-4b and Waterflooding

A base case having fixed well locations with simple waterflooding was run and compared with SP flooding process with well placement optimization (Case-4a) and SP flooding process without well placement optimization (Case-4b). Well placement configuration for the base case and Case-4b remains the same. Table 5.86, Figs. 5.83 and 5.84 showed the summary of Case-4a, Case-4b and waterflooding for best, median and worst realizations for Reservoir Model-2. The incremental UR values are calculated by comparing each of Case-4a and Case-4b with waterflooding.

It is evident from the results that there is an increase in the ultimate recovery after the implementation of stochastic optimization techniques. An increase of around 5.55% to 8.52% is observed when SP flooding is optimized without well placement optimization. However, SP flooding with well placement optimization showed increase in ultimate recovery in the range of about 7.49% to 17.50%.

Table 5.86: Comparison of Case-4a, Case-4b and Waterflooding

Reservoir Model	Stochastic Technique	Solution Type	SP Flooding with WPO (Case-4a)	SP Flooding without WPO (Case-4b)	Water flooding	Incremental UR(Case-4a)	Incremental UR(Case-4b)
						%	%
Reservoir Model-2	CMAES	Best	0.5585	0.5158	0.4753	17.50	8.52
		Median	0.5468	0.5155	0.4753	15.04	8.46
		Worst	0.5375	0.5039	0.4753	13.09	6.02
	DE	Best	0.5362	0.5155	0.4753	12.81	8.46
		Median	0.5294	0.5043	0.4753	11.38	6.10
		Worst	0.5109	0.5017	0.4753	7.49	5.55
	IWO	Best	0.5427	0.5154	0.4753	14.18	8.44
		Median	0.5337	0.5151	0.4753	12.29	8.37
		Worst	0.5263	0.5141	0.4753	10.73	8.16

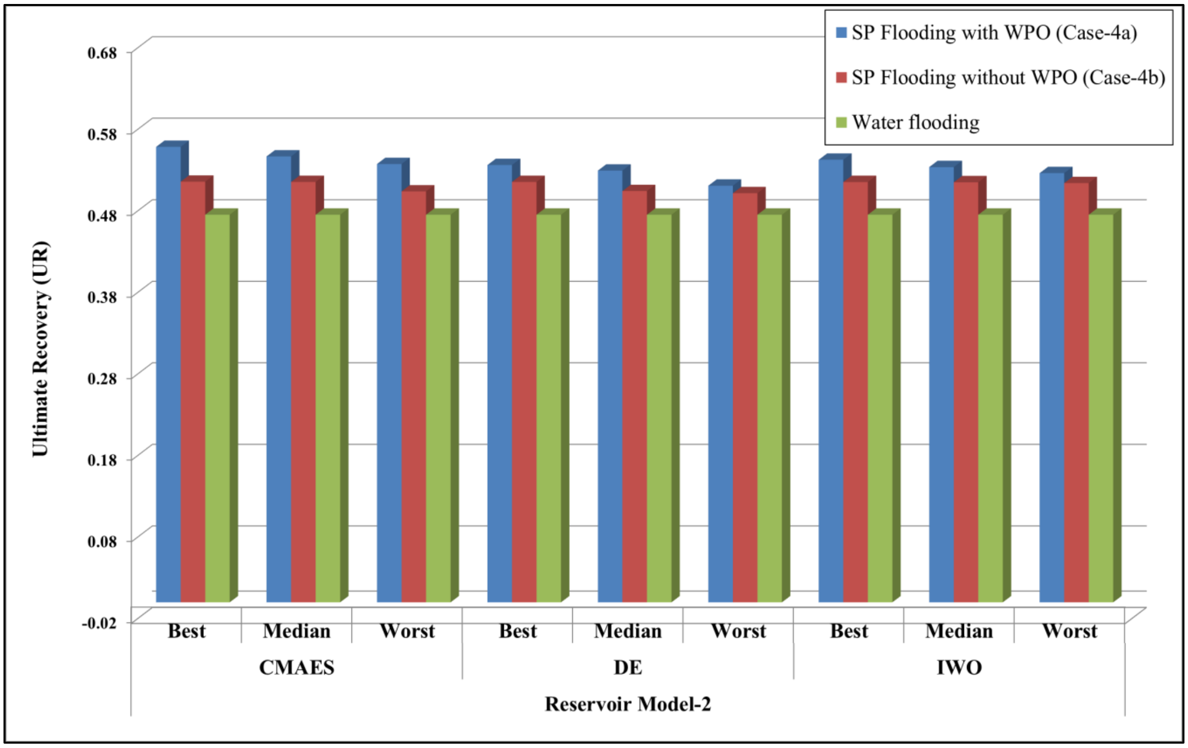


Figure 5.83: Comparison of Case-4a, Case-4b and Waterflooding

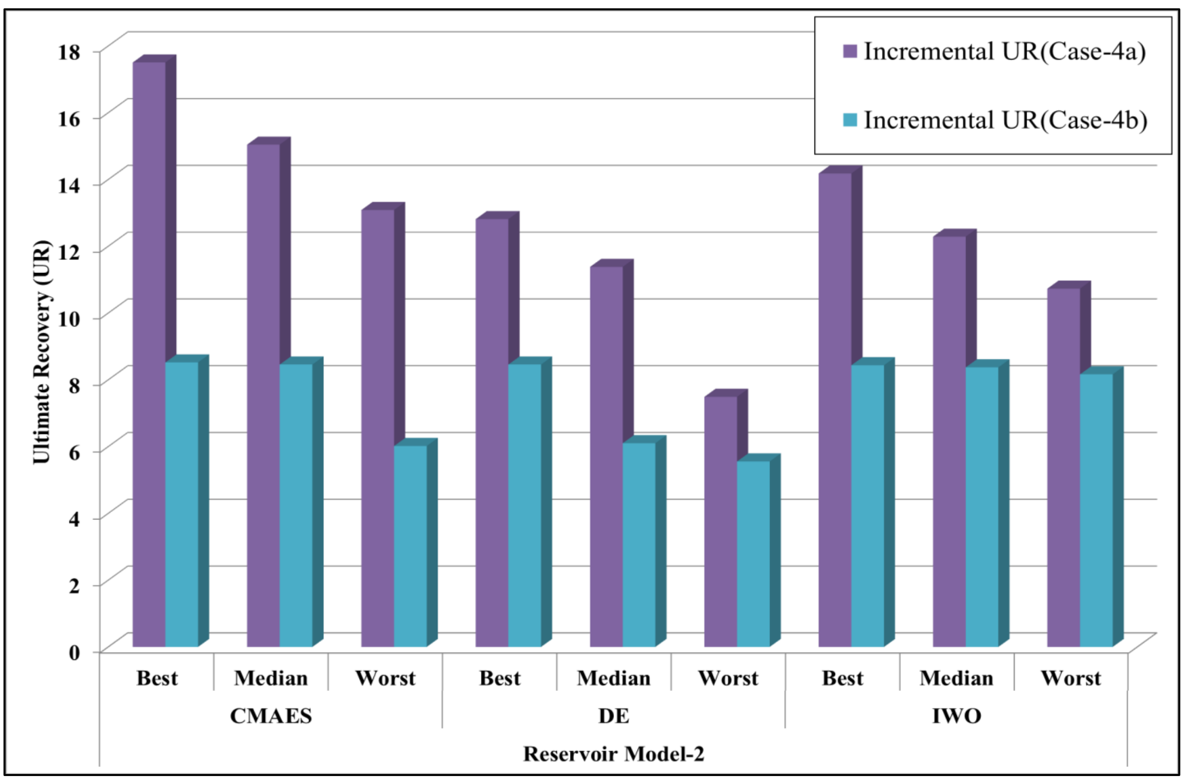


Figure 5.84: Incremental UR from Case-4a, Case-4b

CHAPTER 6

CONCLUSIONS

Based on the results and discussions in Chapter 5, it is evident that the use of stochastic evolutionary techniques increase the NPV and UR as compared with the base case discussed. Furthermore, these techniques are compared on the following criteria.

NPV

CMAES performed better than DE and IWO in all discussed realizations for surfactant-polymer flooding with well placement optimization for channeled reservoir (Case-1a) and in all realizations of fully heterogeneous reservoir (Case-2a and 2b). This is due to the comprehensive search ability and continuous conversion towards the optimized solution of the CMAES. CMAES and IWO tend to improve continuously to search for the optimized solution while DE showed a trend of early conversion mostly to a sub-optimal solution in most of the cases discussed in chapter 5.

UR

CMAES performed better than DE and IWO in almost all discussed realizations for surfactant-polymer flooding with and without well placement optimization for channeled reservoir (Case-3a & 3b) and for fully heterogeneous reservoir (Case-4a & 4b). Furthermore, for channeled reservoir model (Case-3a and 3b), DE performed better than IWO for ultimate recovery prediction however IWO showed better results than DE for the fully heterogeneous reservoir case (Case-4a and 4b). The UR results show that the effect of variability in the reservoir properties on ultimate recovery is better captured by CMAES which results in high ultimate recovery values.

Convergence

CMAES and IWO showed continuous improvement in convergence with small steps that caused these techniques to perform better than DE in most of the cases discussed in chapter 5. However, DE showed early convergence that caused it to result in sub-optimal solution in most of the cases discussed in chapter 5.

Consistency

The three algorithms remained almost consistent for almost all cases.

EOR process Selection

The three techniques showed about the same EOR process selection. Most of the optimized results indicate the need for the initial waterflood period to be followed by surfactant flooding and then polymer flooding for the two reservoirs considered in this research. Furthermore, there are few realizations in which the optimized value of surfactant and/or polymer is very low and cannot be used in practice. This can be explained as the artifact of the optimization process that is seeking for a maximum solution even if the increment is very small and for practical purposes will not be implemented.

Well Placement

The results of well placement are discussed for NPV and UR separately. This is because in this research we found out that the well placement is the most important factor in improving the NPV and UR of the reservoir. Furthermore, it is also concluded that the well placement for cases involving maximization of NPV is different than that of the maximization of UR.

Placement of producers and injectors around the periphery of the reservoir in the channels having high and low permeability values respectively proved to be the best configuration for NPV maximization in channeled reservoir (Reservoir-1). The reason for placing production wells in high permeability area is to recover as much hydrocarbon as possible so that it will increase the NPV for the production life under consideration. The overlapping of injection wells or production wells represent the high injection or production rate requirements in that particular area.

For channeled reservoir (Reservoir-1), peripheral injection is proved to be an inefficient injection scheme for UR maximization. High UR values are obtained when the injectors and producers are uniformly placed in high and low permeability zones. This will help to avoid early water breakthrough and improve the sweep efficiency. Furthermore, the majority of the injectors should be placed in high permeability zones because the injection of chemicals can plug the low permeability zones much earlier than the allocated time for chemical injection.

For fully heterogeneous reservoir (Reservoir-2), peripheral injection scheme is proved to be the best injection scheme for UR maximization. Furthermore, for NPV maximization of fully heterogeneous reservoir (Reservoir-2), the production wells should be well distributed in the reservoir but have an appreciable distance from the injection wells. It is also noted that the placement of the injectors and producers is greatly influenced by the permeability distribution pattern in the reservoir.

REFERENCES

- Ahmed M. Shehata, TPS/Cairo University, Ahmed Ghatas, Mahmoud Kamel, Ahmed Aly, TPS, Ahmed Hassan, PICO, 2012, SPE 151952 - Overview of Polymer Flooding (EOR) in North Africa Fields – Elements of Designing a New Polymer/Surfactant Flood Onshore - Case Study
- Ahmed Y. Bukhamsin, SPE, Saudi Aramco/Stanford University; Mohammad Moravvej Farshi, SPE; Khalid Aziz, SPE, Stanford University, 2010, SPE – 2010, Optimization of Multilateral Well Design and Location in a Real Field Using a Continuous Genetic Algorithm.
- Aanonsen, S.I., A.L. Eide, and L. Holden. 1995. SPE – 30710, Optimization Reservoir Performance Under Uncertainty with Application to Well Location.
- Abhijit Samanta; Achinta Bera; Keka Ojha; Ajay Mandal; 2012, Comparative studies on enhanced oil recovery by alkali–surfactant and polymer flooding.
- A.R. Mehrabian and C. Lucas, 2006; ‘A novel numerical optimization algorithm inspired from weed colonization’, Ecological Informatics1(2006) 355-366, 2006 Elsevier
- A. R. Mallahzadeh, H. Oraizi and Z. Davoodi-Rad, 2008; ‘Application of Invasive Weed Optimization Technique for Antenna Configurations’, Progress In Electromagnetics Research, PIER 79, 137–150, 2008
- Aniruddha Basak, Siddharth Pal, Swagatam Das, Ajith Abraham and Vaclav Snasel, 2010, ‘A Modified Invasive Weed Optimization Algorithm for Time-Modulated Linear Antenna Array Synthesis’, Evolutionary Computation (CEC), 2010, IEEE

- Bariş Gűyagűler, SPE, Roland N. Horne, SPE, (Stanford University) Leah Rogers, SPE, (Lawrence Livermore National Laboratory) Jacob J. Rosenzweig, (BP-Amoco), 2000, SPE – 63221, Optimization of Well Placement in a Gulf of Mexico Waterflooding Project.
- Binitha S and S Siva Sathya, 2012, International Journal of Soft Computing and Engineering (IJSCE) ISSN: 2231-2307, Volume-2, Issue-2, May 2012, 'A Survey of Bio inspired Optimization Algorithms'.
- Bangerth, W., H. Klie, M. Wheeler, P. Stoffa, and M. Sen, 'On optimization algorithm for the reservoir oil well placement problem', Computational Geosciences, 10, 303-319, 2006
- Bittencourt, A. and R. Horne, Reservoir development and design optimization, in Proceedings of the 1997 SPE Annual Technical Conference and Exhibition, 5-8 October 1997, San Antonio, Texas, 1997
- C.G. Zheng, SPE, B.L. Gall, SPE, H.W. Gao, SPE, A.E. Miller, and R.S. Bryant, SPE, BDM Petroleum Technologies, 2000, SPE 64270 - Effects of Polymer Adsorption and Flow Behavior on Two-Phase Flow in Porous Media
- Cuong T. Q Dang, SPE, Zhangxin Chen, SPE, University of Calgary, Ngoc T.B. Nguyen, SPE, Wisup Bae, SPE, Sejong University, Thuoc H. Phung, Vietsovpetro JV, 2011, SPE – 147872, Development of Isotherm Polymer/ Surfactant Adsorption Models in Chemical Flooding.
- Chatzis, I., and Morow, N.R., Correlation of Capillary Number Relationship for Sandstone. SPEJ, 1984, October: 555-562

- Christian Igel, Nikolaus Hansen, and Stefan Roth, 2007, Evolutionary Computation, Volume 15(1): 1-28, ‘Covariance Matric Adaptation for Multi-objection Optimization’
- D.O. Shah, University of Florida, Gainesville, Florida, R.S. Schechter, University of Texas at Austin, Austin, Texas, 1977 ‘Improved Oil Recovery by Surfactant and Polymer Flooding’
- De Groot, M., 1930, Flooding Process for recovering oil from Subterranean Oil Bearing Strata, U.S. Patent No. 1,823,439
- De Groot, M., 1930, Flooding Process for Recovering Fixed Oil from Subterranean Oil Bearing Strata, U.S. Patent No. 1,823,440
- D.Y. Ding, SPE, IFP, 2008, SPE – 113525, Optimization of Well Placement Using Evolutionary Algorithms.
- Dejean J.P., and G. Blanc. 1999. SPE - 56696, Managing Uncertainties on Production Prediction Using Integrated Statistical Methods.
- David Levitt, Stephane Jouenne, Igor Bondino, Jean-Philippe Gingras, and Maurice Bourrel, Total, 2011, SPE – 150566, The Interpretation of Polymer Coreflood Results for Heavy Oil.
- D.Y. Ding, 2008, SPE 113525, ‘Optimization of Well Placement Using Evolutionary Algorithms
- Emerick, A., E. Silva, B. Messer, L. Almeida, D. Szwarcman, M. Pacheco, and M. Vellasco, Well placement optimization using a genetic algorithm with non linear constraints (SPE-118808), in SPE Reservoir Simulation Symposium, 2009

- Feng Xu, Xiao Guo, Wanbin Wang, Nan Zhang, Sha Jia, Xiaoqin Wang, State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, 2011, SPE 145036 – Case Study: Numerical Simulation of Surfactant Flooding in Low Permeability Oil Field.
- Fahim Forouzanfar, SPE, Gaoming Li, SPE, and A.C. Reynolds, SPE, U. of Tulsa, 2010, SPE – 135304, A Two Stage Well Placement Optimization Method based on Adjoint Gradient.
- Gary Pope, University of Texas at Austin, 2011, R&D Grand Challenges: 'Recent Development and Remaining Challenges of Enhanced Oil Recovery
- Guo, G., and R.D. Evans. 1993, SPE – 26676, An Economic Model for Assessing the Feasibility of Exploiting Naturally Fractured Reservoir by Horizontal Well Technology.
- Gűyagűlar, B., 2003. Optimization of Well Placement and Assessment of Uncertainty. Ph.D. Thesis, Stanford University, Stanford, CA.
- Guillaume Collange, Stéphane Reynaud and Nikolaus Hansen, 2010, American Institute of Aeronautics and Astronautics, 'Multidisciplinary Optimization of Expendable Launcher Family'
- Holbrook, O.C., 1958, Surfactant-Water Secondary Recovery Process, U.S. Patent No. 3,006,411.
- Holm, L.W. and Bernard, G.G., 1959, Secondary Recovery Water Flood Process, U.S. Patent No. 3,082,822.
- H. Atkinson, 1927, U.S. Patent No. 1,651,311.
- Hassani, H., Sarkheil, H. and Foroud, T., Karimpooli, S., 2011, ARMA 11-443, A Proxy Modeling Approach to Optimization Horizontal Well Placement

- Hossein Hajimirsadeghi, Amin Ghazanfari, Ashkan Rahimi-Kian, Caro Lucas, 2009, 'Cooperative Coevolutionary Invasive Weed Optimization and its Application to Nash Equilibrium Search in Electricity Markets', 2009 World Congress on Nature & Biologically Inspired Computing (NaBIC 2009)
- Hongjiang Lu, 2004,PHD Dissertation, 'Improving Oil Recovery(IOR) with Polymer Flooding in A Heavy-Oil River-Channel Sandstone Reservoir'
- Handels, M., M. J. Zandvliet, D. R. Brouwer, and J. D. Jansen, Adjoint-based well placement optimization under production constraints, SPE-105797, in SPE Reservoir Simulation Symposium, 2007
- Istvan Lakatos, Janos Toth, Tibor Bodi, and Julianna Lakatos-Szabo, U. of Miskolc, and Paul D. Berger and Christie Lee, Oil Chem Technologies, 2007, SPE 106005 - Application of Viscoelastic Surfactants as Mobility-Control Agents in Low-Tension Surfactant Floods.
- Ilya Loshchilov, Marc Schoenauer, and Michele Sebag, 2011, Springer-Verlag Berlin Heidelberg, 'Not All Parents are Equal for MO-CMA-ES'
- Katsanis, E.P., Krumrine, P.H., Falcone Jr., J.S., Chemistry of Precipitation and Scale Formation in Geological Systems, paper SPE 11082 presented at the 1983 SPE Oilfield and Geothermal Chemistry Symposium, Denver, 1-3 June.
- Karthik Kamaraj, SPE, Gouyin Zhang, SPE, Yi Liu, SPE, and R.S. Seright, SPE, New Mexico Petroleum Recovery Research Center, 2011, OTC – 22040, Effect of Residual Oil Saturation on Recovery Efficiency during Polymer Flooding of Viscous Oils.

- Karaboga, D., and Okdem, S.: “A Simple and Global Optimization Algorithm for Engineering Problems: Differential Evolution Algorithm,” Intl. XII Turkish Symp. On Artificial Intelligence and Neural Networks–TAINN 2003.
- Kokal, Sunil, ‘Enhanced Oil Recovery: A Short Course, EOR Screening’ at Saudi Aramco, 2013
- Lampinen, J.: “Solving Problems Subject to Multiple Nonlinear Constraints by the Differential Evolution,” In: Radek Matousek and Pavel Osmera (eds.) 2001. Proceedings of MENDEL 2001, 7th Intl. Conference on Soft Computing, June 6-8 2001, Brno, Czech Republic, pp.50-57. ISBN 80-214-1894-X.
- Lampinen, J., and Zelinka, I.: “Mixed Integer-Discrete-Continuous Optimization by Differential Evolution Part 1: the Optimization Method,” In: Osmera, Pavel (ed.) 1999. Proceedings of MENDEL’99, 5th Intl. Mendel Conference on Soft Computing, June 9-12 1999, Brno, Czech Republic, pp. 71-76. ISBN 80-214- 1131-7.
- Mian, A.M., 2002a; ‘Project Economics and Decision Analysis’, Volume I: Deterministic Models, Tulsa: PennWell.
- Milton J. Rosen, 1989, ‘Surfactants and Interfacial Phenomena’, second edition
- Nakajima, L., and D.J. Schoizer. 2003. SPE - 81031, Automated Methodology for Field Performance Optimization Developed with Horizontal Wells
- Najafabadi, N.F., Delshad, M., Sepehrnoori, K., Nguyen, Q.P. and Zhang, J. 2008. Chemical Flooding of Fractured Carbonates Using Wettability Modifiers, Paper SPE 113369-MS presented at the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, 19-23 April.

- Nawaf I. Sayed Akram, Saudi Aramco and Daulat Mamora, Texas A&M University, 2011, SPE 149106, ‘Simulation study on surfactant-polymer flood performance in fractured carbonate reservoir’
- Nikolaus Hansen, 2011, ‘The CMA Evolution Strategy: A Tutorial’
- Nikolaus Hansen, 2011, INRIA (INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE) ‘Injecting External Solutions Into CMA-ES’
- O. Badru and C. S. Kabir, SPE 84191, Well Placement Optimization in Field Development
- Ozdogan, U. and R. N. Horne, Optimization of well placement under time-dependent uncertainty, SPE Reservoir Simulation and Engineering, 9(2), 135-145, 2006
- P. Gao, SPE, and B. Towler, SPE, University of Wyoming, and Y. Li, and X. Zhang, PetroChina, 2010, SPE – 129590, Integrated Evaluation of Surfactant-Polymer Floods.
- Riley B. Needham, APE, Phillips Petroleum Co., Peter H. Doe, SPE, Phillips Petroleum Co., 1987, ‘Polymer Flooding Review’.
- R.S. Seright, SPE, New Mexico Petroleum Recovery Research Center, 2010, SPE 129899 - Potential for Polymer Flooding Reservoirs with Viscous Oils
- Schlumberger, Eclipse Technical Description Manual, 2010
- Seifi, A., and M.B. Kazemzadeh. 2008. Metamodeling and optimization of the accumulated outflow from a fractured hydrocarbon reservoir
- Storn, R. and Price, K.: “Differential Evolution - a Simple and Efficient Adaptive Scheme for Global Optimization over Continuous Spaces,” Technical Report TR-95-012, ICSI, March 1995.

- Storn, R.: “Differential Evolution Design of an IIR-Filter with Requirements for Magnitude and Group Delay,” IEEE International Conference on Evolutionary Computation ICEC 96, pp. 268 - 273, Technical Report TR-95-026, ICSI, May 1995.
- Storn, R. and Price, K.: “Minimizing the real functions of the ICEC'96 contest by Differential Evolution,” IEEE Conference on Evolutionary Computation, Nagoya, 1996, pp. 842–844.
- Storn, R.: “System Design by Constraint Adaptation and Differential Evolution,” Technical Report TR-96-039, ICSI, November 1996a.
- Storn, R.: “On the Usage of Differential Evolution for Function Optimization,” NAFIPS 1996b, Berkeley, pp. 519 - 523.
- Shaya Karimkashi and Ahmed A. Kishk, 2010; ‘Invasive Weed Optimization and its Features in Electromagnetics’, IEEE Transactions on Antennas and Propagation, Vol. 58, No. 4, April 2010 1269
- Sarma, P. and W. H. Chen, Efficient well placement optimization with gradient-based algorithm and adjoint models, SPE, 112257, in Proceedings of the 2008 SPE Intelligence Energy Conference and Exhibition, 2008
- Wang, C., G. Li, and A. C. Reynolds, Optimal well placement for production optimization, SPE-111154, in Proceedings of the 2007 SPE Eastern Regional Meeting, 2007
- Yefei Wang; Fulin Zhao; Baojun Bai, SPE; Jian Zhang; Wentao Xiang; Xianjie Li; Wei Zhou, China University of Petroleum, East China, China; Missouri University of Science and Technology, USA; China National Offshore Oil Cooperation, China, 2010, SPE

127391 - Optimized Surfactant IFT and Polymer Viscosity for Surfactant-Polymer Flooding in Heterogeneous Formations.

- Yang, Zhen-Yu and Chen, Guang-Yu, 2004, Petroleum Geology and Oilfield Development in Daqing, Current Status and Prospect of Combination Flooding at Home and Abroad
- Yeten, B., L.J. Durlosky, and K. Aziz. 2002. SPE - 77565, Optimization of Nonconventional Well Type, Location and Trajectory.
- Yeten, B., L. J. Durlofsky, and K. Aziz, Optimization of nonconventional well type, location and trajectory, in Proceedings of the 2002 SPE Annual Technical Conference and Exhibition, 29 September – 2 October 2002, San Antonio, Texas, 2002.
- Zhang, K., G. Li, A. C. Reynolds, J. Yao, and L. Zhang, Optimal well placement using an adjoint gradient, Accepted by Journal of Petroleum Science and Engineering, 2010
- Zyed Bouzarkouna, Didier Yu Ding and Anne Auger, ECMOR XIII-13th European Conference on the Mathematics of Oil Recovery, Biarritz, France, 10-13 September 2012 'Using Evolution Strategy with Meta–models for Well PlacementOptimization'
- Zyed Bouzarkouna, Anne Auger and Didier Yu Ding, GECCO'11, July 12-16, 2011, Dublin, Ireland,'Local-Meta-Model CMA-ES for Partially Separable Functions'.
- Z. Bouzarkouna, D.Y. Ding and A. Auger, SPE 143292, INRIA, 'Partially Separated Meta-models with Evolution Strategies for Well Placement Optimization'

VITAE

Name: Hassaan Ahmed

Date of Birth: July 7, 1985

Present Address: KFUPM P. O. Box 8609, King Fahd University of Petroleum and Mineral, Dhahran-31261, Saudi Arabia

Permanent Address: H. No. R-546, Block 14, F.B. Area, Karachi, Pakistan

Email Address: hassaanahmed85@gmail.com

Educational Qualification:

M.S (Petroleum Engineering)

November, 2013

King Fahd University of Petroleum & Minerals,

Dhahran, Saudi Arabia.

B.E. (Mechanical Engineering)

December, 2007

NED University of Engineering & Technology,

Karachi, Pakistan.